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P000 599	Carmonette-Division Battle Model Interface.
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P000 605	Analytical Simulation of Attacks Involving Helicopter/Guided Missile Systems.
P000 606	Analytic Models of Air Cavalry Combat Operations.
P000 607	TOS(2) (Tactical Operations System) Simulation Model.
P000 608	Differential Models of Combat in Cities.
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P000 612	The Automated Assembly of Simulation Models.
P000 613	A General Computer Program for Use in Determining Track Width Plow-Minefield Effectiveness Criteria.
P000 614	Mixed Minefield Modeling.
P000 615	Battlefield Related Evaluation and Analysis of Countermine Hardware (BREACH).
P000 616	AVVAM-1 (Armored Vehicle Vulnerability Analysis Model) Vulnerability Sensitivity Studies.
P000 617	Sensitivity Analysis of a Weapon Effectiveness Model.
P000 618	A Mathematical Model for Assessment of Chemical Weapons Systems.
P000 619	On Reliability Growth Modeling.

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AD#:		TITLE:
	P000 620	Mass Core Memory Unit Decision Risk Analysis.
	P000 621	SAM-D Firing Doctrine Model.
	P000 622	Lines of Communications Targeting for Ground Operations.
	P000 623	A Hierarchical Structure of Models for the Analysis of Land Mobility Systems.

FOREWORD

The Twelfth Annual U.S. Army Operations Research Symposium was held on 3-5 October 1973. For eleven years these symposia were sponsored by the Chief of Research and Development. It was my privilege as the Assistant Chief of Staff for Force Development to sponsor the twelfth symposium in this series. I was gratified by the enthusiastic attendance, the quality of the program, and the spirited discussions of technical matters of great importance to the Army. I think all will agree that it was a highly successful meeting.

These proceedings contain most of the papers presented at the symposium. Some of the presentations are not included here either because the paper was not formalized or the speaker chose not to have his remarks published. > to pg iv

The symposium was planned, organized, and chaired by Mr. Abraham Golub, Scientific Advisor to the ACSFOR, assisted by Mr. E. B. Vandiver III of the Office of the Scientific Advisor, OACSFOR. We are all indebted to them for their outstanding efforts on our behalf. We also appreciate the valuable assistance of those who participated in the various sessions of the symposium.

E H Almquist

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ACKNOWLEDGEMENTS

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A HIERARCHY OF MODELS TO AID IN THE DESIGN OF WEAPON SYSTEMS

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The purpose of this paper is to describe the hierarchy of mathematical models in use at the Rodman Laboratory to aid in the design of weapon systems, and to project the future growth and application of this hierarchy.

Some years ago, the weapon design and development process consisted solely of the trial and error method: A technological advance applicable to weaponry would be incorporated into a conceptual system design; a prototype would be built and tested; on the basis of test failures, the system would be redesigned; a new prototype would be constructed; and the process would be repeated until a "workable" system evolved. This trial and error process was exemplified in the development of the Garand rifle. The redesign, the prototype, and test cycle continued from 1918 through 1936, a total of 18 years.

The necessity for and the benefits from prototype development and testing are obvious; however, increasing weapon complexity and cost have made the pure trial and error method infeasible. The engineer must now produce a system design for a prototype that will have an excellent chance of "working" initially and that will require only minor design change, if any.

A variety of tools and techniques have been developed to enable the design engineer in meeting this challenge. These include more sophisticated drafting equipment, breadboard and component testing techniques, and computer software packages and graphical aids. Many tools and techniques are in use at the Rodman Laboratory; however, particular emphasis is being focused upon mathematical modeling.

Advances in computer technology and increased access to the computer have made possible the development and application of a broad spectrum of computer models. As an aid in describing this modeling hierarchy, the models have been divided into three broad categories or levels, ~~as depicted in Figure 1~~: engineering and subsystem modeling, performance modeling, and effectiveness modeling. As indicated by the dotted lines, the differences in the types of modeling are not distinct, i.e., considerable overlap exists.

ENGINEERING AND SUBSYSTEM MODELING

The first category represents a large number and variety of the more traditional and detailed engineering design models generally made from sets of formulas and equations which were once left only to the engineer and his slide rule for solution. The more basic examples include models of heat transfer, kinematic and dynamic relationships, and stress analysis by the finite element method. Many of these are available through standard computer software packages. One such example, NASTRAN (NASA Structural Analysis), is a general purpose structural analysis model developed for use

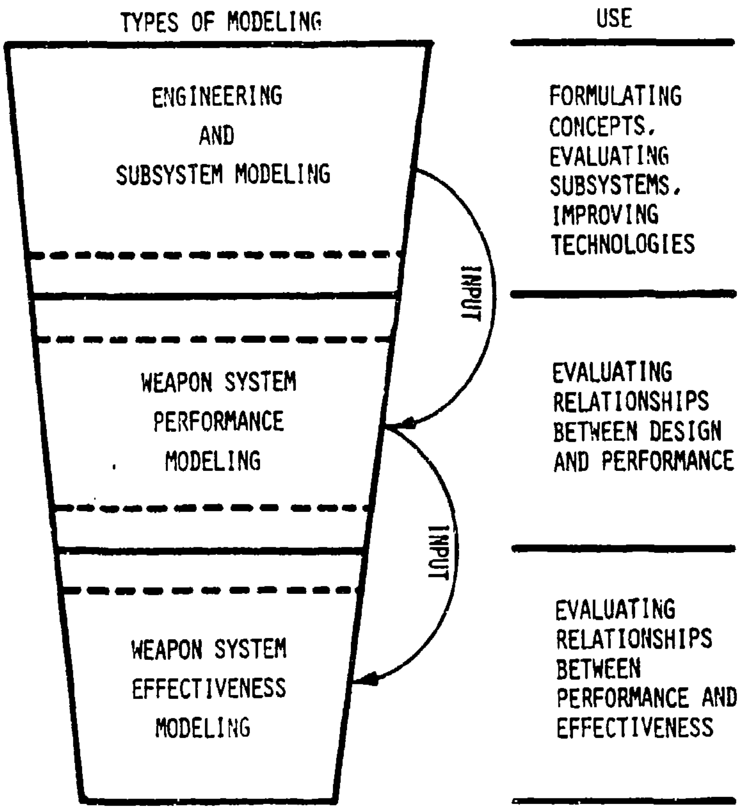

Figure 1. MODELING CATEGORIES

in analyzing stresses, natural frequencies, frequency responses and deflections.

A variety of specialized engineering models have been developed to simulate a weapon subsystem or component. Examples include models of gas flow, spring dynamics, recoil mechanisms, and both interior and exterior ballistics. Although some of these models are generally applicable to weapon systems ranging from a small arms rifle to an 8-inch artillery piece, the majority are unique to a specific system. Attempts have been made to model the total mechanical operation of a weapon system; such is the case with the Parametric Design Analysis (PDA) model which was developed and applied in analyzing accelerations and forces in the Squad Automatic Weapon System.

The engineering and subsystem models are applied to a variety of uses. Their applications include proving design feasibility, optimizing component and subsystem design, finding the causes for and the prediction of component failures, and in general aiding in the detailed design decision process. These models also provide the knowledge and data necessary for developing the second category of modeling, the performance models.

PERFORMANCE MODELING

A weapon performance model simulates a single total weapon system

performing one or more of its intended functions. For example, in the case of an armored weapon system such as a tank, the general functions which are performed both actively and passively include:

- detecting enemy weapon systems
- firing at enemy weapon systems
- moving
- communicating
- being detected
- receiving incoming enemy fire

The performance of these functions is dependent upon the specific design of the weapon system, and each function impacts upon its combat effectiveness. Although interdependencies exist among the majority of the functions, each function can be independently simulated mathematically and the performance of a given function can be related to variations in the design of the weapon system.

For the function of vehicle movement, mobility performance models have been developed by the Tank Automotive Command which produce V-ride limits, speed, acceleration, and obstacle crossing capabilities of armored weapon systems under a variety of terrain conditions. These models are sensitive to changes in the design of the weapon system.

The Ballistics Research Laboratory has developed a tank vulnerability model by which the effects of incoming enemy rounds are assessed and the probability of kill data generated. If the configuration of the target vehicle were changed, corresponding changes would be reflected by the model in the kill probabilities.

Because of function interdependencies, the simultaneous simulation of more than one function may be required. Weapon system firing performance may impact upon its detectability; its mobility may impact upon its vulnerability, detection, and firing capabilities. This latter relationship between moving and firing prompted the development of the HITPRO fire-on-the-move performance model.

HITPRO deterministically simulates the dynamic gun pointing error of a ground mobile weapon system as it moves over a known terrain. The elements simulated within HITPRO are shown in Figure 2. A firing tank is simulated moving along a test course defined as a series of circular arcs with bumps similar to the Aberdeen Proving Ground test course. The turns and bumps are variable inputs; the speed of the firing tank is defined by input data and can be specified for any portion of the course; and the direction of the target is in a straight line.

The component factors influencing the aiming error of a tank main gun while it is being fired on the move include the terrain, suspension-hull interaction, hull-turret interaction, human operation, and the gun. For an accurate gun aim, the stabilization system with gunner response must counteract gun movements due to vehicle motion. The impact of the terrain on vehicle motion is modeled in two parts: (1) The linear motion including the forward acceleration, velocity, and turning rate is calculated on the basis of the input course programmed as a series of constant-velocity and constant turning-rate segments (2) The three components of angular motion

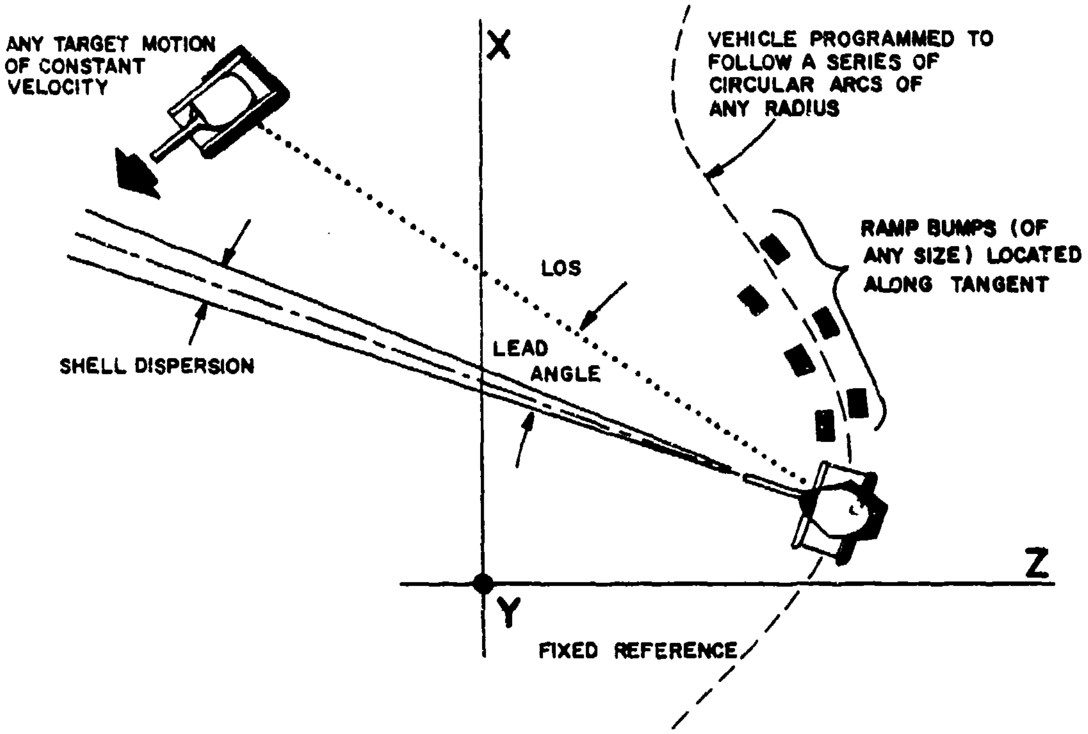

Figure 2. HITPRO FIRE-ON-THE-MOVE PERFORMANCE MODEL

and small amplitude vertical motion are also calculated and terrain roughness, recoil forces and torques, acting on the suspended vehicle are considered. These vehicle movements require the stabilization system to be responsive in both azimuth and elevation. The simulation includes provision for drive motor characteristics and load torque disturbances caused by friction, imbalance, vehicle angular acceleration, and firing recoil. The stabilization system reacts to inputs from the gunner hand-station, gun-mounted rate gyros, elevation and traverse tachometers, and hull and turret rate gyros. Currently, the HITPRO model simulates the XM19 ballistic computer used in the M60A2 tank. The computer provides lead angle and superelevation corrections. When a computer has not been incorporated into the vehicle, these inputs are provided by the gunner submodel. The dynamic response of the gunner to observed gun pointing errors through the reticle is simulated. Also, the following factors are considered: the decision to reset lead angle, the judgment that tracking is smooth enough to make a lead reset measurement, and the judgment that aiming is sufficiently close to the target to justify firing. When the gunner commands a firing, the nominal trajectory of the shell and the nominal miss at the target (including target motion during shell time of flight) are computed. The shell dispersion pattern is integrated over the target area to determine a hit probability. A wide variety of data can be output from HITPRO including the hit probabilities for shots, vehicle speed, gun aiming direction, sight reticle position, and other signals, all as functions of time. HITPRO was used to predict firing

results of an M60A2 test at Aberdeen in late 1970, and results indicated that erroneous lead solutions would be applied. Initial results on the Aberdeen bump course confirmed the HITPRO prediction, and appropriate corrections were made to the XM19 ballistic computer.

Performance models are in general subject to field test validation. A comparison of actual test data and HITPRO model predictions for the elevation of the main gun relative to the tank hull for a 14-second segment of travel over the Aberdeen bump course shown in Figure 3. An analysis of this and other data collected at Aberdeen has been used as a basis for validating the HITPRO model.

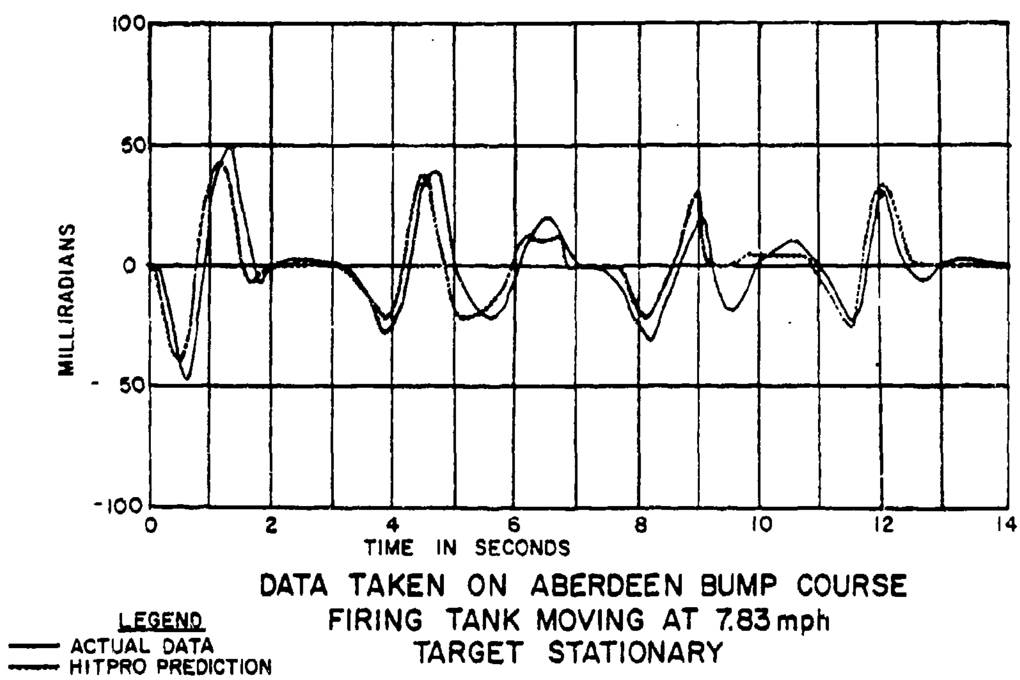

Figure 3. HITPRO VS TEST DATA

Since the primary mission of the Rodman Laboratory is gun design, the emphasis in performance modeling has been focused upon the weapon firing function, primarily aiming error. Weapon firing performance models in use at the Laboratory include SEGAWS (System Evaluation, Gun Aircraft Weapon Simulation), GADES (Gun Air Defense Effectiveness Study) Dynamics model, and unnamed artillery and small arms models. Although their applications are varied, these performance models have been used primarily to identify critical design parameters and to relate changes in these parameters to variations in firing performance. Other applications include predicting and optimizing system performance, finding the causes for and the prediction of system failures, and in general conducting design-performance trade-offs.

EFFECTIVENESS MODELING

The third category or level of modeling is represented by the effectiveness models. Basically, an effectiveness model simulates an engagement in which the weapon systems are subjected to a realistic battlefield environment depicting their intended use. These models, in general, provide for variations in terrain, threat, unit organization and weapon system performance, and output measures of effectiveness such as missions accomplished, killing rates, and exchange ratios.

Numerous examples of effectiveness models exist including relatively simple one-on-one duals, high resolution battalion simulations, and low resolution multidivision war games. Those models having the greatest application in aiding the design process are the more detailed, high-resolution simulation models such as IUA (Individual Unit Action), CARMONETTE, and DYNTACS (DYNamic TACtical Simulation).

DYNTACS, the most comprehensive of the high-resolution battalion-level models, was made operational at the Rodman Laboratory in February of 1970. This model was developed by the Systems Research Group of Ohio State University to provide a highly complex stochastic simulation of armored combat in a midintensity situation. DYNTACS was originated in 1965 under the guidance of the CDC Armor Agency with initial emphasis focused upon conventional tank systems. An early form was modified for the Missile Command to evaluate alternative forms of the Shillelagh missile system. The model has recently been augmented to include artillery support, crew-served weapons, counterbattery fire, aerial platforms, air defense weapons, scatterable mines and mine countermeasures. The complete model with all extentions is referred to as DYNTACS-X.

The foremost characteristic of DYNTACS is its detailed representation of individual weapon firepower, mobility, protection, and detection capabilities and their interactions with the terrain. Fundamental concepts are emphasized such as cover, concealment, and fields of fire. To provide this detailed simulation, extensive input data are required. As depicted in Figure 4, the input data fall into three broad categories: environment, operations, and design parameters. The environment comprises a continuous 5 by 10 kilometer area with overlays in which vegetation, trafficability, obstacles, cover, and concealment are described. The operations data are provided through an input scenario which includes force organizations, criteria for selecting attack routes, firing assignments, firing priorities, formations and withdrawal routes, and other data requiring military judgment. Since the original intent in the development of DYNTACS was to provide a tool capable of evaluating alternative armored weapon system designs, extensive engineering data are required as input. For each ground vehicle type "played," the mobility characteristics required as input include:

- vehicle gross weight
- length of track in contact with the ground
- width of track
- ground clearance
- location of the center of gravity
- final drive efficiency

. final drive ratio
. pitch diameter of the sprocket
. tracked or wheeled vehicle

<u>Curves Representing</u>
. maximum speed vs. surface inclination
. engine speed vs. transmission speed
. transmission speed vs. transmission torque

Similarly, for each weapon type, the firepower characteristics include:

. ammunition supplies
. ammunition priorities on the basis of target and range
. muzzle velocities and effective ranges
. maximum range and velocity for on-the-move firing
. probability of a misfire
. time to clear a misfire
. load time (standard deviation and median)
. lay time (standard deviation and median)
. probability of sensing projectile impact points
. neutralization period resulting from a hit by tank main gun
. rapid fire ballistic characteristics
. main gun ballistic properties
. conditional kill probability given a hit

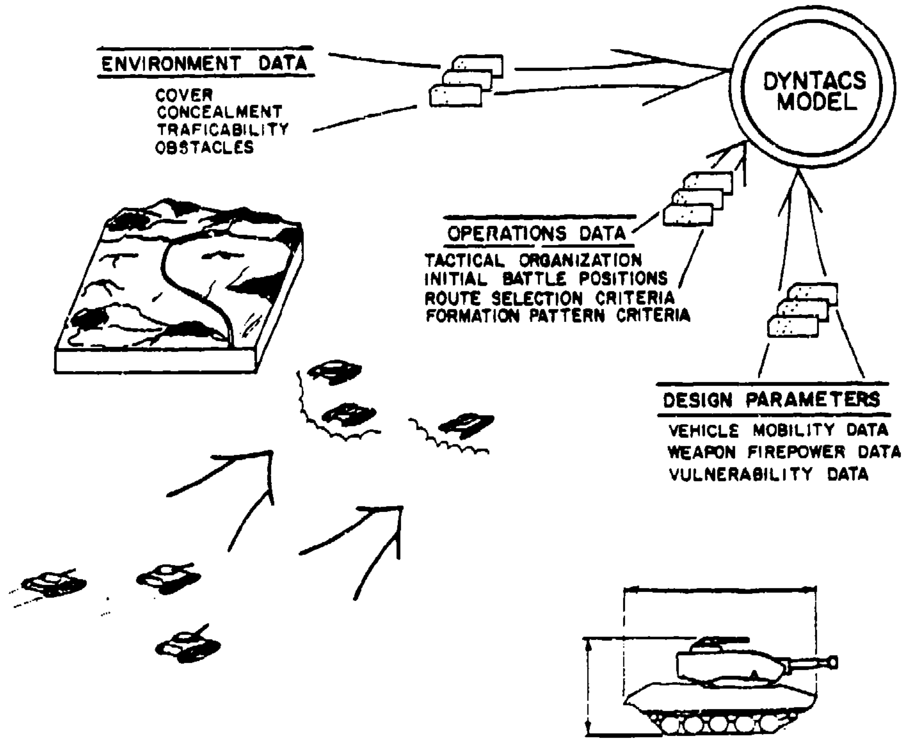

Figure 4. DYNTACS INPUT DATA CATEGORIES

The DYNTACS model is operated on the basis of event-sequencing, that is, moving and firing events of the weapon systems are ordered in time based on the duration of each event. Basically, when an element such as a tank is selected for an event, communications are processed on appropriate nets, line of sight and detections are determined, route and formation are identified, a target and projectile are selected, movement is calculated for a fixed time or distance, and finally the effects of the shot are assessed on the target. The duration of this event is added to the clock time of the element and results in the start time for the element's following event. The next element to be processed is then selected by sequencing logic on the basis of least clock time. Indirect fire artillery is incorporated by sequencing events for firing batteries, fire direction centers, and forward observers. Targets of opportunity are dynamically constructed by forward observers, and on-call fires are requested when required. Time delays to request and deliver artillery fires are represented, and the lethal and suppressive effects are assessed for each impacting round.

DYNTACS is, by far, the largest and most complex model at Rodman Laboratory. To complement its comprehensive and rather specialized capabilities, the Laboratory obtained and made operational the more simplified Bonder/IUA model. This model is an adaptation of the Bonder methodology to the Individual Unit Action (IUA) simulation scenarios. It is an extension of the Lanchester analytic formulations in which the stochastic play of weapon effects is replaced by a generalized system of differential equations. The attrition rate equations are numerically solved on the basis of measurable weapon system parameters. Aggregation of the weapons of the same type in the same general location and treatment of them as a single group reduces the running time of the model. Weapons of different types or weapons of the same type, but at different locations, are not aggregated. Since this model is deterministic, replications do not have to be performed. Because the Bonder/IUA model is relatively inexpensive to operate, it is ideally suited as a screening tool for performing parametric analyses.

Besides DYNTACS and the Bonder/IUA models, several simplified one-on-one dual models have been developed. These include the GADES Fire Unit Model used to evaluate air defense guns against high performance aircraft and attack helicopter models.

Traditionally, effectiveness models have been utilized to evaluate and compare alternative conceptual weapon systems to determine which is the most combat effective. This was demonstrated in a 1970 application of DYNTACS to support the Project Manager's office for M60 tanks in an evaluation of M60A1 tank mobility improvements. More recently, effectiveness models have been utilized to parametrically analyze weapon system performance characteristics to determine which characteristic or combination of characteristics has the greatest impact on weapon system effectiveness. The Bonder/IUA model was recently exercised in support of the MBT Task Force to parametrically analyze levels of tank firepower, vulnerability and silhouette size. Another example is the current Rodman Laboratory application of DYNTACS to support the Family of Scatterable Mines (FASCAM) study. In this study, parametric data variations were made to mine probabilities of kill against vehicle tracks and belly, and to the

number of mines for each artillery projectile. Thus, the most effective mine design characteristics were determined.

FUTURE MODEL APPLICATIONS

In almost every instance, each model within the engineering and subsystem, performance, and effectiveness modeling categories has been developed and applied independently. This use will, undoubtedly, continue. However, because of the number of models being developed and the interrelationships which exist among these models, coordination of their future development and application is fast becoming necessary.

Model development efforts within the Rodman Laboratory are on-going in all three modeling categories. Engineering and subsystem models are continually under development to meet specialized design analysis requirements. Primary emphasis on performance modeling is in the modification and the development of weapon firing performance models. Modification of the HITPRO model has recently been initiated to simulate the firing of a rapid-fire weapon from a mechanized infantry vehicle. Other major performance modeling efforts under way include the development of a comprehensive helicopter firing performance model and the continued development of the GADES Dynamics model. The emphasis on effectiveness modeling is the continued modification of DYNTACS. Extension of the model has been initiated to provide for the simulation of close-support aircraft and cannon-launched guided projectiles (CLGP). With these model additions, the DYNTACS model can be used to analyze the effectiveness of a large number of armored, helicopter, artillery, and air-defense weapons for which the Rodman Laboratory has responsibility.

The application of this hierarchy of models in the design process requires considerable model interface. Models within each category must be compatible both in engineering detail and in input/output data requirements. Engineering and subsystem models should generate data in the proper format for direct input to performance models. In addition, the performance models should provide data for direct input to effectiveness models. Within the modeling responsibilities of the Rodman Laboratory, steps are being taken to provide this compatibility.

With the development of appropriate models which satisfy necessary interface requirements, utilization of the modeling hierarchy may soon be feasible to guide the design of weapon systems. One possible concept for the design process application is illustrated in Figure 5. For an existing weapon system, such as the M60A1 tank, a design specification data base (Tech. Data Package) exists and includes numerous drawings and extensive engineering details such as component weights and dimensions necessary for the production of a hardware item. The raw inputs required by the performance models are derived from this data base. When performance models are exercised against the data base, the functional performance of this weapon system is described through performance data output. An analysis of this performance data may result in recommended design changes which increase performance. The engineering and subsystem models would then be exercised and on the basis of results obtained, the system would be redesigned, and specific changes would be made in the design specification

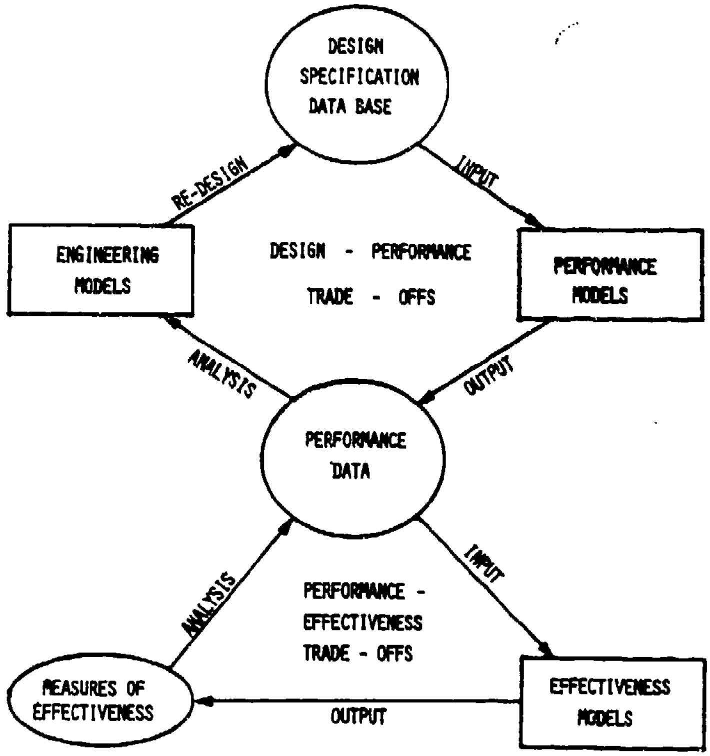

Figure 5. MODELING APPLICATIONS IN THE DESIGN PROCESS

data base. The application of the performance, and the engineering and subsystem models, and the analysis of output data constitutes the design/performance trade-off process. Alternative design changes can be evaluated with respect to their impact upon the functional performance of the weapon system. For example, if a design change were to be made resulting in more armor protection, the vulnerability performance model output would show decreased vulnerability; however, the mobility model output would show decreased mobility.

The next problem to be resolved in the design process is that of determining the optimal mix of performance characteristics. As indicated by the example of added tank armor, the question arises, Is it better to have a highly mobile and lightly armored tank or the opposite, a less mobile and heavily armored tank? The trading-off of one performance parameter for another involves the iterative application of effectiveness models. Data by which the performance of a given weapon system is described are provided as input to an effectiveness model. The effectiveness model is then exercised and provides, as output, measures of combat effectiveness reflecting the combat worth of the given weapon system. An analysis of the effectiveness data may indicate potential payoffs to be gained by modification of the performance of the weapon system. This change would be reflected in the performance data and evaluated by the exercising of the effectiveness model to again determine the resulting effectiveness. The application of the effectiveness models in this way

constitutes the performance/effectiveness trade-off process. On the basis of the previous example, the vulnerability and mobility trade-off can be performed in such a way as to identify the optimal performance mix which results in the most effective weapon system.

Pure application of effectiveness models to optimize performance would undoubtedly result in a weapon system which, from a design point of view, is infeasible. Therefore, the total weapon system design process must include the combining of both the design/performance and the performance/effectiveness trade-off processes. As a result of this combination, detailed weapon system design changes can be evaluated in terms of combat effectiveness gains or losses. Through the exercising of the engineering and subsystem models, a weapon system can be redesigned to reflect a feasible design change and appropriate updates can be made to the design specification data base. By use of the modified data base as input, the performance models can then be exercised to predict the performance of the modified weapon system. These performance data are then input to the effectiveness model which results in a relative measure of the effectiveness of the modified weapon system. In this way, alternative design changes can be evaluated with respect to their impact upon the overall combat effectiveness of the system.

In summary, the weapon system design process is far from being totally automated. Many required models have not as yet been developed and many existing models are cumbersome and inadequate. However, the direction is clear. The planned development and the intelligent application of a hierarchy of models have already proved to be an aid in the design, development, and fielding of the current complex and effective weapon systems. As new weapon system requirements arise and new technologies emerge, complex modeling hierarchies will play an even greater roll in guiding the weapon system design process.

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TACTICAL EFFECTIVENESS TESTING OF ANTITANK MISSILES

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ABSTRACT

In December 1970, the Program Budget Division 464 established the Army's Study on Tactical Effectiveness Testing of Antitank Missiles (TETAM). This study includes the generation of valid data using field experimentation and the use of these data in combat simulations. The combination of these two efforts will allow for the assessment of the effectiveness of three U.S. antitank missiles; TOW, SHILLELAGH, and DRAGON and two foreign missiles; the British SWINGFIRE and the French-German MILAN. This paper discusses the nature of the field experimentation being conducted and presents some results which have emerged.

I Introduction

The Tactical Effectiveness Testing of Antitank Missiles (TETAM) is part of a larger antitank missile (ATM) system test program, Program Budget Decision (PBD) 464. Although the acronym TETAM covers more than the field experimentation part of the ATM Study, that acronym will be used for both the experimentation and the study in this paper. As part of this continuing effectiveness testing of ATM, the purposes of TETAM are to:

Contribute to the assessment of combat effectiveness of the SHILLELAGH, TOW, DRAGON, SWINGFIRE and MILAN under simulated combat conditions.

Provide data for use as input to pertinent subroutines of certain US Army high resolution predictive combat models, primarily DYNTACS, CARMONETTE, and IUA.

Verify, to the extent possible with data produced by the TETAM Experiment pertinent subroutines of these US Army high resolution predictive combat models.

The experiment is being conducted over a two-year period as shown below.

Phase	Time Frame
IE	March - June 1972
IA, B, C, L	September - December 1972
II	April - June 1973
III	October - December 1973

Phase I of the experiment obtained intervisibility data between attacking armored elements and defensively employed antitank weapons, and data on the performance of ATM systems in acquiring attacking armored elements as targets. Phase II obtained performance data on attacking armored elements in acquiring defensively employed ATM systems as targets. The results from Phases I and II will be used with predictive models, and to assist in the selection of force-mixes for Phase III, which is a two-sided, non-live fire, near real-time loss assessment, ATM system-versus-tank experiment.

Each phase and sub-phase will be discussed separately.

II. Phase I, TETAM

A. Phase IE:

The specific objective of Phase IE was to obtain line-of-sight, i.e., intervisibility, data between a number of simulated, defensively employed SHILLELAGH, TOW, and DRAGON missile systems and a simulated, advancing tank force in an assumed mid-intensity European conflict setting.

Since ATM systems are line-of-sight limited, previous studies were examined to determine how terrain limits the use of these systems.

This examination showed that previous studies lacked a sufficient base of reliable data upon which conclusions could be drawn. Phase IE, by exhaustively gathering verified data from 12 FRG sites, has supplied this base of data.

The experiment was conducted in the FRG during March-June 1972. Twelve sites were utilized for field execution. Five of the sites were located within a 40 km radius of FULDA, GERMANY. A sixth site was located in the Seventh Army Training Area at HOHENFELS, GERMANY. The remaining six sites were located in the BERGEN-HOHNE-SOLTAU training areas, south of HAMBURG, in the NORTH GERMAN PLAIN area.

On each of these 12 sites, ten realistic tank trails were laid out. These trails represented the path an attacking tank may take if it were part of a force attempting to take the hill on which the ATM positions were located. The 30 to 36 ATM positions on each site were selected to represent positions from which one of the three missile systems under study may fire at the attacking force.

At 25 meter intervals on each tank trail, determination was made of which of the 30 - 36 ATM positions had intervisibility with the trail. This intervisibility was determined for each of three heights above the ATM position (4', 6' and 10') and two heights above the trail (4' and 7'). If intervisibility did not exist, what was in the way was recorded. Since each trail was from 3000 to 5000 meters long, a little arithmetic shows that data were collected on well over one-half million pairs of points.

The results of Phase IE are the topic of another paper in this symposium.

B. Phase IA, B, C, L:

In preparation for phases IA, B, and C, intervisibility data were collected on two sites at Hunter Liggett Military Reservation in California. The procedure for this data collection was similar to that in Phase IE. A significant difference was that on one of the sites at HLMR two sets of trails were laid out, one representing a rapid approach route and the other representing a deliberate approach in which maximum use was made of cover and concealment.

Phase IA was designed to examine the effectiveness of evasive maneuvers on the part of the attacking tanks.

This Phase was executed following completion of the intervisibility work, so it was known which viewing point on each path was intervisible with each ATM panel. Stakes marking each 25-meter viewing point on the rapid approach paths were left in place to allow tanks to follow the paths and as a key to initiate evasive maneuvers.

Beginning at the opposite end of the site, a tank advanced toward the ATM positions, following exactly a tank trail laid for the rapid approach route. As a tank approached a viewing point known to be intervisible with a particular ATM panel, a controller directed the team at that panel to detonate an artillery simulator in front of the panel. He also notified the tank commander that he was about to be "fired" upon from his left, right or center. When the tank crew detected the simulator, they took watever evasive action the tank commander felt would most quickly break LOS with the ATM position which had "fired" on him. The tank commander was allowed to maneuver up to 20 seconds.

The results of the experiment showed that the median distance of travel required to break line-of-sight on that piece of terrain was about 70 meters.

Phase IB consisted of two similar experiments concerning detection of approaching vehicles. In the first part of Phase IB three types of vehicles were configured to appear like threat tanks, anti-tank guided missile launch vehicles, and APCs. A random mix of six of these vehicles advanced toward the ATM positions, following exactly the rapid approach paths. It was therefore known where intervisibility segments began and ended on each path. Each vehicle was instrumented to provide continuous position data.

Players, located at ATM positions, scanned the area where the armored vehicles were advancing, using either the unaided eye or binoculars. When a player detected an advancing vehicle, he announced "DETECT" to the data collector, who immediately recorded the detection. This information along with previously known intervisibility patterns allows the calculation of time to detect given an opportunity. Analysis of these data is included in another paper in this symposium.

In the second part of Phase IB, the detection as described above was followed by identification of the target and simulated fire upon it. The trigger pull activated a bore-sighted camera which photographically recorded the event. This, in addition to giving time to fire data, provided assurance that a target had indeed been detected. Results showed median times of two seconds to identify and 8 to 11 seconds to engage (depending upon weapons system).

The objective of Phase IC was to obtain data on the times required for and the problems encountered in passing a target from a person detecting it, through normal channels in a platoon, to an ATM weapon crew for possible engagement. This process was termed "handoff."

Rather than recreate the entire chain of command, nine handoff pairs were formed consisting of a platoon leader handing off to a squad leader, a rifleman handing off to a squad leader, or a squad leader handing off to an ATM gunner. The two team members were located separately and communicated by telephone.

Six vehicles, configured as threat tanks, antitank guided missile launch vehicles, and APCs, advanced toward the ATM positions in three zones. One member of each team scanned the site until he detected an advancing vehicle. He then handed off the vehicle by identifying it and describing its location. The other member of the team then attempted to detect the same vehicle.

Results of this experiment showed that 51 to 68% of the handoffs were successful (depending on range) and mean time required when the handoff was successful was between 18 and 31 seconds.

In Phase IL, intervisibility data were gathered at two sites in Ft Lewis, Washington. The procedure was the same as for Phase IE.

III. Phase II - TETAM

The second major phase of TETAM was primarily concerned with detecting and bringing under fire the defensive ATM positions by the attacking force. The three parts of Phase II dealt with different detection cues, such as flash, missile flight, and movement.

A. Phase IIA:

The objective of Phase IIA was to obtain data on the ability of attacking armor crews to detect, identify, localize, and pinpoint ATMs with either random sighting or missile launch signature as possible detection cues. The missile launch was simulated with approved signature simulators. The SHILLELAGH and DRAGON simulators provided dust, smoke, flash, and noise. The TOW simulator fired a slug as well.

M60 tanks and M551 vehicles were used as threat armor vehicles. Each vehicle operated in one of three modes: advancing unbuttoned, stationary unbuttoned, or stationary buttoned.

The defensive array consisted of tactically deployed SHILLELAGH, M113-mounted TOW, and DRAGON ATM systems. In addition, six positions in the defensive area were designated as artillery simulation positions.

For convenience of execution, trials were conducted in a series of movement intervals (MI). As each MI began, the threat crews were allowed to scan the defensive area, and the advancing vehicles moved toward it. At predetermined time intervals, the Experimentation Control Center directed each ATM to fire a missile launch signature simulator; 12 simulators were fired during each MI. Interspersed with the ATM firings, personnel at the artillery positions detonated 1/4 pound blocks of TNT, simulating incoming artillery and presenting distracting detection cues to the threat array. The threat crews were required to detect, identify, localize, and pinpoint as many ATMs as possible. In the case of the advancing unbuttoned M551s, detection and localization were accomplished while the vehicle was still moving; they then came to a short halt to pinpoint and engage. Times that these events occurred were recorded by the data collector on each vehicle; "firing" the main gun at an acquired ATM activated the movie camera, taking a film strip of the ATM/IR beacon "fired" upon. This film provided the pinpoint accuracy data and the identification of the particular ATM pinpointed.

Following completion of each MI threat crews were moved out of view of the defensive area and the ATMs changed positions preparatory for the next MI.

Results of Phase IIA show that the TOW is the easiest to detect followed by the SHILLELAGH and the the DRAGON. The percent of launches which resulted in detection were from 32 to 47 for TOW (depending on which armor element was attempting to detect), from 22 to 35 for SHILLELAGH and from 18 to 29 for DRAGON.

B. Phase IIB:

Phase IIB generated the most interest of all phases of TETAM. This was mainly because in this phase we fired actual (inert) missiles at stationary targets and also at a manned moving heavily armored tank. Although the success of the missile system operators in hitting the target received much attention, that was not the primary objective of this phase.

The primary objective was the same as Phase IIA, with missile flight added as a possible detection cue. Secondary objectives were to obtain hit data on evasive and stationary targets, and on the ability of the TOW and MILAN to track an evasive tank.

The threat array consisted of the stationary, buttoned M60 tanks used in Phase IIA. Stationary targets were wooden panels with the silhouette of a T62 tank in half-hull defilade on them. The evasive target tank (ETT) was a modified, manned, M48A3 tank.

In Phase IIB, one DRAGON and two each SHILLELAGH, TOW, and MILAN systems made up the defensive array. In later trials SWINGFIRE systems replaced the MILANs, the DRAGON was not used, and SHILLELAGH and TOW fired signature simulators.

During a trial, each system which was firing missiles fired one at the ETT and three at stationary targets.

Results indicate that the flight of the missile seldom provided a cue to those trying to detect the ATM positions. The percent of firing in which the missile was reported as a cue were none for DRAGON, 5 for TOW, 7 for MILAN, 9 for SHILLELAGH and 13 for SWINGFIRE. Hit data are classified.

C. Phase IIC:

The objective of Phase IIC was to obtain data on the physical exposure of ATM systems when engaging an attacking armor element. The ATM systems tested were the TOW, SHILLELAGH, DRAGON, MILAN, and 106mm Recoilless Rifle.

Each ATM system started in a defilade, or "hide," position. On command of a data collector collocated with the ATM, the crew moved the weapon forward to a firing position. Once in the firing position, they laid on a target panel downrange and simulated firing and tracking a round. At the end of the time of flight, the data collector announced "Impact," which was the signal for the crew to move the weapon back to the hide position.

Data similar to that collected in Phase IIA were recorded. The purpose was to determine if the movement had a significant effect.

The results showed movement was a significant cue. The percentage of all detections for which movement was reported as a cue was 9 for the DRAGON, 53 for the TOW and 61 for the SHILLELAGH.

A small side experiment in Phase II was conducted to see how well the TOW and MILAN could track an agile target, the XR-311 "Dunebuggy." Tracking film is available but has not been analyzed.

IV. Phase III:

Part IIIA is exploratory experimentation to verify operational procedures and to confirm the design of subsequent parts. One of the primary design objectives of exploratory experimentation is to verify that the specified force mixes will provide a balanced force structure. It may become necessary to adjust the structure of the defensive or threat forces based on the results of exploratory experimentation.

The keystone in the design for Phase III is based on the execution of Part IIIB. All other parts of Phase III will be conducted under all or a selected portion of the conditions under which Part IIIB will be conducted.

TETAM has six objectives. Phase III will address Objectives 5 and 6 only. These objectives are:

5A - To obtain performance data on antitank missile systems in defensive positions when engaging an attacking armored element in simulated combat.

5B - To obtain performance data on attacking armored elements when engaging defensively employed antitank missile systems in simulated non-live fire combat.

6B - To obtain data to assess the effect of countermeasures on antitank missile systems performance.

6C - To obtain data to assess what counter-countermeasures should be taken to overcome aggressor countermeasures.

This phase is being conducted between September and December 1973.

Following the basic trials of Phase IIIB additional trials will be run in which the primary objectives are:

IIIC - Evaluation of SWINGFIRE Gunner-launcher separated concept.

IIIE - To allow the DRAGON to attack from the flank.

IIIF - To evaluate an Indirect Fire Casualty Assessment System.

IIIG - To evaluate the systems in night combat.

IIIH - To evaluate the contribution of scatterable mines.

(Don't worry about IIID as it was cancelled.)

V. Summary

The conduct of field experimentation to obtain data on all possible combinations of conditions in support of effectiveness evaluations is

beyond reasonable resources and time consideration. A logical means to obtain such quantities of information is through a program whereby field experimentation data can be obtained for input to, and use in validating computer simulation models. If the latter is successful, the models can then be used to generate additional credible data for those conditions not obtained during experimentation. This integrated field experiment-model program approach has been used in designing all phases of the experiment.

To further the exchange of information and improve the understanding of the antitank missile capabilities of the NATO forces, an Ad Hoc Evaluation Group for Antitank Missile Testing has been formed with representatives from the United States, Great Britain, France, and the Federal Republic of Germany. TETAM is the first antitank missile experiment to be conducted since the formation of the Ad Hoc Group. The MILAN and the SWINGFIRE concept are evaluated in both Phases II and III.

Complete reports of Phases I and II are available through Headquarters, US Army Training and Doctrine Command. Reports of Phase III will be available by 1 March 1974.

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CARMONETTE-DIVISION BATTLE MODEL INTERFACE

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In the Equal Cost Firepower study conducted by Research Analysis Corporation for ACSFOR in 1971 and 1972, a technique was developed for using the results of the CARMONETTE simulation for small unit battles to assess the outcomes of battle in the Division Battle Model (DBM) games. This technique was designed to replace the classical firepower score technique of assessing losses in war games. The results of 518 CARMONETTE replications were used as inputs to a regression analysis to derive the coefficients for a set of assessment equations used in the DBM ground combat routine.

This approach was successful and resulted in creditable casualty assessments in the DBM games in which the losses on each side were a function of the mixes of opposing weapons, tactics, and other factors considered. However, this method had some limitations which precluded its use in the GRC-OAD 1973 work program.

First, the regression procedure requires an extremely large amount of data in order to avoid colinearities among the independent variables. The 518 replications mentioned above represent 74 different treatments of seven replications each. Even this large number of treatments, made possible only by combining the resources for two large studies, is barely adequate when different terrains and postures are considered.

The second, and more important, limitation is that the results of a battle assessment can only be attributed to the mix of weapons involved; target kills by cause cannot be identified.

For the COMCAP II and SCAT II projects, in process at this time for the Department of the Army, a solution for the CARMONETTE-DBM interface has been developed which produces a specific killer-victim matrix for each battle assessed.

The present technique is derived from the COMAN model, developed by Dr. Gordon M. Clark of Ohio State University in 1969, and has been titled COMANEX. COMANEX is a deterministic model based on Dr. Clark's extensions of the classical Lanchester theory of combat. It is a satellite model; it must be used in conjunction with a high resolution combat simulation—in this case, CARMONETTE. Using data from several treatments (battles) of CARMONETTE, COMANEX can assess the results of similar battles at a very small fraction (about .003) of the computer time required for CARMONETTE.

As mentioned above, COMANEX is based on extensions of classical Lanchester theory. Lanchester's two laws of combat are shown in (1) and (2) in terms of differential equations.

$$\frac{dR}{dt} = -bB \qquad \frac{dB}{dt} = -rR \qquad (1)$$

$$\frac{dR}{dt} = -\ bBR \qquad \frac{dB}{dt} = -\ rRB \qquad (2)$$

where

R = Number of Red weapons at a given time, t

B = Number of Blue weapons at a given gime, t

b = Rate at which a single Blue weapon kills Red weapons

r = Rate at which a single Red weapon kills Blue weapons.

Equations (1) represent Lanchester's Square Law, which assumes that all targets are visible to all firers, and equations (2) represent the Linear Law which assumes that no targets are visible. These equations are for homogeneous forces (one type of weapon on each side), but can be generalized easily so as to apply to heterogeneous forces. For example, the Linear Law equation for the attrition of Red type 1 weapons would be

$$\frac{dR_1}{dt} = -\ b_{11}B_1R_1 - b_{21}B_2R_1 - \cdots - b_{n1}B_nR_1 \qquad (3)$$

where

b_{i1} = the rate at which a Blue type i weapon kills Red type 1 weapons

B_i = Number of Blue type i weapons

R_1 = Number of Red type 1 weapons.

Dr. Clark extended the Lanchester formulation by adding a parameter p representing the probability of <u>non-acquisition</u> of a single Red weapon and a set of variables, R_i', defined as the number of Red weapons of priority higher than R_i. The COMAN equation for the attrition of Red type i weapons is then

$$\frac{dRi}{dt} = -\ b_{1i}B_1(1-p^{R}i)\ P^{R_i} - \ldots - b_{ni}B_n\ (1-P^{R_i})\ P^{R_i}, \qquad (4)$$

where b_{ji} is now defined as the rate at which a Blue type j weapon kills Red type i weapons given that at least one type i is detected and that no weapon of higher priority is detected. For the case, p = 0, this formulation reduces to the Square Law; as p approaches 1, the formulation reduces to the Linear Law. Thus, this set of equations covers the range of combat situations intermediate between the extremes of total target visibility and total invisibility.

COMAN was developed by Dr. Clark as a means of expanding the data base of DYNTACS outputs for tank/antitank battles. In his formulation he assumed that every weapon on each side had the same priority sequence. When we at GRC considered adopting the model as a part of DBM, where assessments were made of about 15 weapon types on each side, it was obvious that this

assumption would not hold. Thus, the original COMANEX computerized assessment model was identical to the COMAN formulation with the added capability of being able to input a discrete priority list for each type of weapon.

COMANEX comprises two basic sub-programs—the preprocessor and the simulator. As originally envisioned, data from each replication of a CARMONETTE treatment, in the form of time-sequenced casualty histories, were input to the COMANEX preprocessor, which output a set of parameters (b_{ji} and p for the equation above) for each of several discrete time intervals of the battle. These parameters are calculated using the statistical principle of "maximum likelihood." Using this technique, a unique set of parameters is obtained that is "most likely" to have produced the results of the CARMONETTE replications of the original force mix. Conceptually, the procedure is analogous to fitting a curve to a set of observed data points by the method of least squares, although the actual mechanics are quite different. In tests of the model it was found that the results of several CARMONETTE treatments differing in mixes of the several weapon types considered, but having in common such things as posture, terrain, and rate of movement, could form the basis of a single set of COMANEX parameters. A library of such parameters is developed for varying terrains and missions and is stored on tape for use in DBM.

In the early tests of the model, although it usually predicted CARMONETTE outcomes, occasionally battle results were predicted which were clearly unreasonable. These anomolies derived from the assumption that each weapon follows the input priority list slavishly. That is, if more than one type of target is detected, the higher priority will always be engaged. Although this is usually the case, CARMONETTE recognizes the contingency that a lower priority target may be posing a grave threat to a firing weapon, in which case he would logically fire at the threatening target. When this happens, the preprocessor computes a very large kill rate (b_{ji}) against the lower priority target. If in a succeeding extrapolation using this set of parameters the number of higher priority targets is severely reduced, this kill rate dominates the entire battle.

To avoid such occurrences in the conduct of a DBM game, we took a step backward from Dr. Clark's formulation and rewrote equation (4) as

$$\frac{dR_i}{dt} = - b_{1i} B_1 (1-P^{R_i}) - \cdots - b_{ni} B_n (1-P^{R_i}). \qquad (5)$$

This change had the effect of incorporating a sort of firing priority (in terms of fraction of fire at each type of target) into the kill rates. It is recognized that under this formulation one could not extrapolate the parameters from a single treatment of CARMONETTE over as wide a range as was theoretically possible under the original formulation. However, with careful consideration to the CARMONETTE games to be played and the capability to incorporate several games into a single set of parameters, we have had very good results in all tests.

To test the validity of the model in reproducing the results of CARMONETTE games, many comparisons have been made. In every test, COMANEX has produced results quite close to those of CARMONETTE. The results of

one series of such tests are shown in Tables 1 to 6. In this series, six battles represented all possible combinations of three Blue forces (one infantry-heavy, one tank-heavy, and one balanced) and two Red forces (one infantry-heavy and one tank-heavy). All battles had Blue in defense and all were on the same terrain. The output of three of these battles was used to develop a set of COMANEX parameters. These parameters were then used in the COMANEX simulator to reproduce each of the three treatments on which the parameters are based (Tables 1, 2, and 3) and to predict the outcomes of the other three battles (Tables 4, 5, and 6). Results such as these would appear to represent a significant advance over the traditional firepower score method of assessing casualties.

In the current studies, the COMANEX simulator, which actually assesses the outcome of battles, is embedded within DBM as the ground combat subroutine. The DBM gamers specify which numbered units are engaged, the posture (Blue in delay, defense, counterattack, etc.), and break criteria. COMANEX then assesses the results of the battle until a break threshold is reached, or the battle progresses to the end of the CARMONETTE-generated data base. (In practice, DBM battles are seldom permitted to proceed to the point of CARMONETTE termination.) Break criteria include time, personnel casualties, and any combination of equipment losses.

This technique has proven to be an invaluable addition to the conduct of division-level war games. It not only provides assessment on an analytical basis which is intuitively appealing, but it gives the gamers a degree of flexibility impossible to achieve with prior techniques. For example, either or both sides may be reinforced during the course of a battle or the battle may be interrupted at any point for the assessment of an air strike and then resumed. We realize that there are still shortcomings, but while we are working on overcoming them, we feel we have an extremely useful tool representing a large step forward in the state of the art.

Table 1

COMPARISON OF CARMONETTE TREATMENT 3001 AND COMANEX

Blue Losses

Killed by	Tank	TOW	Small Arms
Tank	1/1[a]		
BMP	2/2	1/1	
102 Mortar			3/2
122 HOW			12/12
152 HOW			4/4
122 MRL			0/1

Red Losses

Killed by	Tank	BRDM	BMP	Small Arms
Tank	4/4		6/6	
TOW	6/6	1/1	6/6	
DRAGON	4/4		3/3	
4.2"				1/1
LAW			1/0	
81-mm				1/1
AH	2/2		1/1	
155 How				6/5
8" How				2/2

[a]Number of the left of the slash (/) represents CARMONETTE results; number to the right, COMANEX.

Table 2

COMPARISON OF CARMONETTE TREATMENT 1101 AND COMANEX

Blue Losses

Killed by	Tank	TOW	Small Arms
Tank	5/5[a]		
BRDM	2/2		
BMP	6/6		
MP SAGGER	2/2		
100 AT	1/1		
120 Mortar			1/1
122 How			4/4
152 How			1/1

Red Losses

Killed by	Tank	BMP	Small Arms
Tank	4/4	10/10	
TOW	2/2	2/2	
DRAGON	2/2	1/1	
4.2"			0/1
81-mm			1/1
AH	2/2	1/1	
155 How			2/4
8" How			2/2

[a]Number of the left of the slash (/) represents CARMONETTE results; number to the right, COMANEX.

Table 3

COMPARISON OF CARMONETTE TREATMENT 3201 AND COMANEX

Blue Losses

Killed by	Tank	Small Arms
Tank	3/3[a]	1/1
BMP	1/1	
120 Mortar		0/2
122 How		8/11
122 MRL		2/2

Red Losses

Killed by	Tank	BMP	Small Arms
Tank	7/6	3/3	
TOW	8/8	2/2	
DRAGON	6/5	1/1	
4.2"			1/1
81-mm			1/1
AH	2/2		
155 How			4/4
8" How			1/1

[a]Number to the left of the slash (/) represents CARMONETTE results; number to the right, COMANEX.

Table 4

COMPARISON OF CARMONETTE TREATMENT 2201 AND COMANEX

Blue Losses

Killed by	Tank	Small Arms
Tank	6/6[a]	
BRDM	1/1	
BMP	1/1	
MP SAGGER	1/1	
122 How		7/8
120 Mortar		0/1

Red Losses

Killed by	Tank	BMP	Small Arms
Tank	6/4	3/5	
TOW	6/6	1/2	
DRAGON	5/4		
AH	2/3		
4.2"			1/1
81-mm			1/1
155 How			3/4
8" How			1/2

[a]Number to the left of the slash (/) represents CARMONETTE results; number to the right, COMANEX.

Table 5

COMPARISON OF CARMONETTE TREATMENT 1201 AND COMANEX

Blue Losses

Killed by	Tank	Small Arms	AH
Tank	9/10[a]	1/0	
BRDM	2/2		
BMP	2/2		
MP SAGGER	1/1		
23/4			1/1
120 Mortar		0/1	
122 How		4/4	

Red Losses

Killed by	Tank	BMP	Small Arms
Tank	10/7	6/7	
TOW	3/3	1/1	
DRAGON	3/2		
4.2"			1/1
81-mm			0/1
AH	2/3		
155 How			3/4
8" How			1/1

[a]Number to the left of the slash (/) represents CARMONETTE results; number to the right, COMANEX.

Table 6

COMPARISON OF CARMONETTE TREATMENT 2101 AND COMANEX

Blue Losses

Killed by	Tank	TOW	Small Arms
Tank	3/3[a]		
BRDM	1/1		
BMP	3/4	1/1	
MP SAGGER	1/1		
100 AT	0/1		
120 Mortar			2/1
122 How			5/8
152 How			2/2
122 MRL			0/1

Red Losses

Killed by	Tank	BMP	Small Arms
Tank	2/3	7/6	
TOW	4/4	6/4	
DRAGON	4/3	1/1	
4.2"			1/1
81-mm			0/1
AH	2/2	1/1	
155-mm			5/5
8" How			3/2

[a]Number to the left of the slash (/) represents CARMONETTE results; number to the right, COMANEX.

THEATER FORCE EVALUATION SYSTEM

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INTRODUCTION

BACKGROUND

The FOREWON force planning system, developed by RAC for the Army under the sponsorship of the Assistant Vice Chief of Staff, includes a theater-level combat model called ATLAS. In ATLAS the effectiveness of each combat element is represented by a single number—its firepower score; the strength of a force is found by adding up all the firepower scores; and FEBA movement depends mainly on the ratio of the firepower scores for the two opposing forces. While ATLAS provides a convenient way of representing the action in an entire theater, it is widely recognized that a model of this type does not adequately represent the interactions among the combat arms. In particular, it does not permit study of the balance among the arms in a theater force; and it is severely limited in the study of alternative ways of employing a given force.

Therefore the development of a new Theater Combat Model (TCM) was undertaken, first as a part of the FOREWON research program and later (1970) under ACSFOR sponsorship. The objective of this development was to provide an improved technique for determining theater force capabilities. In particular, the outcome of theater battle was to be properly sensitive to the mixes of combat units on both sides, and was to reflect command decisions concerning missions and allocation of available resources.

Meanwhile, in April 1970 the ACSFOR directed CDC to "develop a conceptual design for the Army in the field [CONAF] which will provide the best Army capabilities attainable within projected levels of resources available during the mid-range period." CDC, in response to this directive, prepared a CONAF study plan consisting of three principal tasks: (1) force design, (2) force costing, and (3) measuring the effectiveness of alternative force designs and operational concepts. CDC itself took on the first two tasks and asked RAC to do the third.

RAC began work on this project in February 1971 and by the end of the year had developed a CONAF Evaluation Model (CEM) based on the TCM, applied the CEM in evaluating 12 different theater forces provided by CDC, and initiated an extensive program of CEM improvements.

This improvement program was continued through most of 1972, culminating in CEM II, which was then applied extensively in the CDC CONAF II study. In March 1973 Army responsibility for CONAF was transferred to the Concepts Analysis Agency (CAA), and CAA has sponsored additional development of the CEM in preparation for theater force evaluation in CONAF III.

PURPOSE OF THIS PAPER

The purpose of this paper is to highlight the principal features of CEM III, outline its structure, and discuss its applications.

CEM III

PRINCIPAL FEATURES

The CEM is a fully-automated, deterministic computer simulation of theater-level, non-nuclear warfare with a continuous FEBA. Once the inputs have been developed and the "Start" button pushed, the simulation proceeds without user intervention.

One of its most important features is the extensive set of decision routines. Periodically during the war a commander's estimate of the situation is made for each unit on both sides, at every echelon from division up to theater, These estimates of the situation are then used as the basis for decisions concerning the assignment of missions and unit boundaries, allocation of fire support, commitment and reconstitution of reserves, assignment of reinforcement units, and allocation of logistic resupply. This feature permits each side to respond tactically to earlier activity of the enemy and assures that forces are employed sensibly.

Combat is resolved in the CEM to brigade-level engagements. The outcome of each engagement is sensitive to the mix of weapons within the combat forces (and Tac Air) on both sides. This feature, together with the spectrum of engagement types generated by the model, makes the outcome of a campaign sensitive to the structure of the theater combat forces.

Campaign tempo and outcome are also quite sensitive to resource expenditure on both sides—casualties, losses of major weapons, and consumption of supplies by class—and to the associated resupply and replacement rates.

Combat across an entire theater can be portrayed for several months; but because of the high-speed computation, a day of combat requires only a few minutes on the CDC 6400 computer.

BASIC MODEL STRUCTURE

Engagements

Combat forces—resolved to brigade level for Blue and division for Red—are deployed initially on a map in which the terrain is resolved into four types, depending on the maneuverability of forces. Type A, for example, affords good cross-country mobility to vehicles, whereas vehicles in Type C terrain are generally road-bound. Type D represents important obstacles such as large rivers.

Once the war starts, combat is assessed periodically across the front in a series of engagements of approximately brigade level. The characteristics of each of these engagements includes the type of

terrain, the type of defensive position (if appropriate), the combat units involved, their missions, and their current status in terms of personnel, major weapons, and supplies on hand. The Blue brigades involved receive varying amounts of support from division and corps cavalry units (which include attack helicopters), division and corps artillery, and close air support. The Red force is treated in a similar, but less detailed fashion.

The current status of each unit is used to develop an effective firepower array for the type of engagement in question, and these arrays are then used in calculating engagement results. Each array represents firepower from six source-classes that could be delivered effectively against three target-classes in this particular type of engagement on this type of terrain. The firepower arrays on each side are then further modified by the availability of appropriate targets on the enemy side in calculating a force ratio, which governs the FEBA movement for this type of engagement in this type of terrain. Equipment losses and casualties are calculated, depending on one side's firepower and the other side's targets; and supply consumption is determined. Status files are then updated, taking into account these losses and consumption and subsequent replacements and resupply.

Determination of Engagement Characteristics

In a sense the remainder of the model, although it is quite complex, can be regarded as a mechanism for determining the characteristics of all engagements—in time and across the battlefield and by combat unit.

The way in which the model does this is shown in Figure 1 in a very highly aggregated form. The primary inputs are (a) the objectives and resources allocated to the theater by the opposing nations, and (b) information related to the outcome of brigade-level engagements (discussed above). The primary outputs are the FEBA location, resource consumption, and status of the opposing forces.

Periodically at each echelon an estimate of the situation is made, and—on the basis of this estimate—missions are selected and resources of various kinds are allocated to subordinate commands. This sequence continues down to brigade level, where the engagement characteristics are specified, and the engagement outcome is computed as outlined above.

For example, consider the box labeled "Blue Corps Commander's Estimate." The Army commander has assigned a sector and allocated certain resources to the corps, and the corps commander must now consider how he can best make use of these resources. Specifically, he must decide what mission to undertake, what sectors to assign to his divisions, how to allocate his corps artillery and cav units among these divisions, and when and where to commit or reconstitute a corps reserve. He makes these decisions on the basis of his knowledge of his own forces, an estimate of enemy forces opposing him (the dashed line indicates imperfect intelligence), and calculations of various alternative results. The army commander went through such a process earlier, and the division commanders will make similar decisions as soon as they receive their resource allocations.

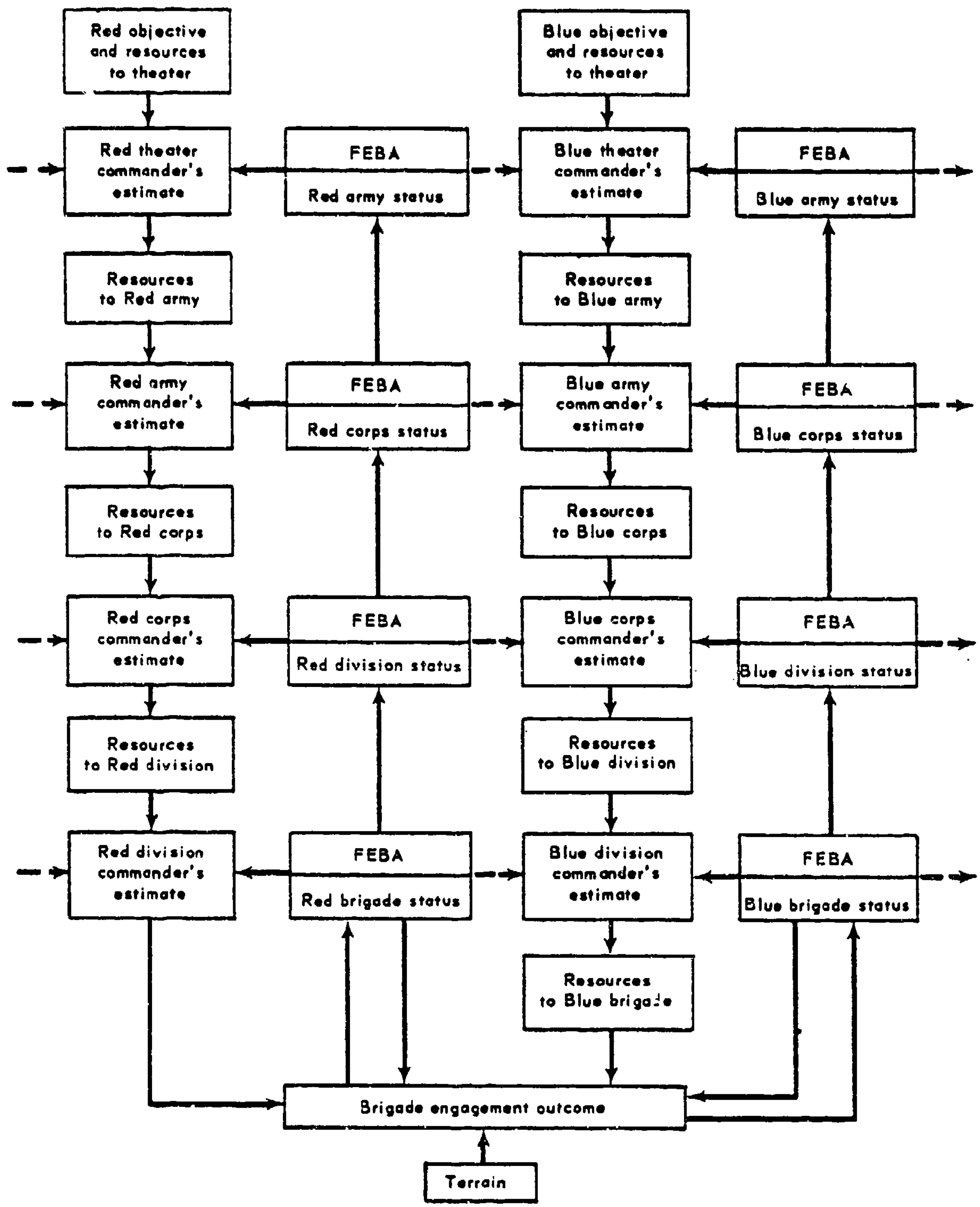

Fig. 1—CONAF Evaluation Model Outline

Note: Dashed lines indicate imperfect intelligence.

The model consists, then, of a set of interlocking cycles, each cycle occurring with a frequency characteristic of that particular echelon. (The frequencies in current applications range from once every 12 hours at division level to once every four days at theater.) The principal model operations at each echelon are as follows:

Theater

Reinforcement artillery battalions assigned to armies
Air battle assessed
Close air support allocated to armies
Replacement personnel, equipment, and supplies allocated
Equipment repaired and wounded treated

Army

Reinforcement divisions assigned to corps
Mission selected and corps sectors assigned
General support artillery and close air support allocated to corps
Reserve corps assigned
Red divisions enter, leave unit replacement pool

Corps

Mission selected and division sectors assigned
General support artillery, close air support, and corps cavalry elements allocated to divisions
Reserve division assigned

Division

Brigade missions selected
General support artillery, close air support, and cavalry elements allocated to brigades
Ground battle assessed
Replacement personnel, equipment, and supplies assimilated by brigade

The tactical air war is fought simultaneously with the ground war, although this is not shown in Figure 1. Periodically the available tactical air sorties are allocated among three general roles—counter-air, and armed reconnaissance and interdiction, and close air support—and aircraft in each role have a different effect on the course of the war. Close air support sorties, for example, are allocated down echelon-by-echelon from theater to brigade, where they contribute directly to the outcome of the brigade-level engagement. Losses are assessed to aircraft in all three roles, and subsequent allocations of aircraft to the roles are based largely on the loss rates experienced, in accordance with the planner's strategy.

Division Cycle

A complete description of CEM operations is beyond the scope of this paper. As a matter of interest, however, in this section the division cycle is described for the Blue side in greater detail, with emphasis on the estimate of the situation and associated decision-making.

Principal Steps. At the beginning of the cycle the division is assigned a sector and given an allocation of cavalry and fire support by corps (based on the corps estimate of the situation). The fire support consists of a number of general support artillery battalions and a number of close air support sorties.

In the next step the division estimate of the situation is made, followed by decisions concerning brigade missions, allocation of cavalry and fire support, and commitment or reconstitution of the division reserve. This step is described in greater detail below.

These decisions by the opposing forces are sufficient for all the engagement characteristics to be specified, and the engagement results are then computed.

Finally, the division receives an allocation of replacements and resupply and reallocates them among its brigades; and the next cycle can begin.

Division Estimate. The estimate of the situation consists of a series of estimated engagement outcomes, based on various hypothetical circumstances. For each brigade on line, the division commander estimates the threat, then asks and answers several "What if" questions.

For each brigade in each hypothetical engagement, the expected engagement characteristics must be established. The commander begins by considering an attack mission for the brigade; and he knows the current status of the brigade and the number of artillery battalions normally in direct support of the brigade.

Next he estimates the corresponding information about the enemy. Estimating an enemy mission is complicated by the fact that a brigade may face elements of more than one division, having different missions. The enemy mission is estimated to be the same as it was last period, provided that it was the same for all units faced. If it was not the same for all enemy units, then a cautious estimate is made. That is, if the assumed brigade mission is attack, then the enemy mission is estimated to be defense; and if the brigade mission is defense or delay, then the enemy mission is estimated to be attack.

In estimating the numbers of enemy combat units of each type, a weighted average is taken of the numbers of each type actually faced in the past two periods. The weighting factors are clearly related to the intelligence capability of the force.

Whenever a unit mission is assumed (or estimated) to be defense, then the type of defensive position must be determined (or estimated). This is done by examining the average FEBA movement across the unit front during the past several periods and comparing it with a threshold. If the actual movement was less than the threshold value, then the unit is considered to have had time to prepare good defensive positions; otherwise, the defense is characterized as hasty. The value used for the threshold depends on the engineer capability of the unit.

Once all the characteristics of the hypothetical engagement have been ascertained, the anticipated outcome is computed in the usual way.

Next, this entire process is repeated three times—each case corresponding to an option open to the division commander. First, he allows the artillery in direct support of the brigade to fire at an increased rate. Second, he assigns a reinforcing role to a fraction of the corps artillery in general support of his divisions. And third, he commits the reserve brigade, dividing up the original brigade frontage. The final result of the estimate of the situation, then, is an estimated outcome for each of these four sets of conditions.

Division Decisions. The most favorable of the four outcomes is identified, together with the least support required to achieve this outcome. If all the outcomes are unfavorable, then a brigade mission one step lower on the aggressiveness scale is considered, and the estimating sequence is repeated. Otherwise the brigade is assigned the assumed mission and is allocated the minimum support needed to achieve the best expected outcome.

The discussion above was based on the assumption that the division has two brigades on line and one in reserve. In case the division has all three brigades on line, one of them is virtually withdrawn and the estimate of the situation is made in the normal way. If the estimate and resulting decisions do not lead to reserve commitment, then the virtual withdrawal becomes actual, and the withdrawn brigade becomes the division reserve. If the estimate does lead to reserve commitment, then the brigade is not withdrawn.

After these decisions concerning the ground forces have been made, the tactical air sorties available for support of the division are allocated. (Note that tactical air played no part in the estimate of the situation.) Generally speaking, close air support sorties are allocated to engaged brigades so as to support strength on offense and weakness on defense.

APPLICATIONS

The CEM measures the performance of a theater force in combat, and it relates this performance to literally thousands of input variables. In particular, it relates force performance to the mix of combat battalions on both sides and the mix of major weapon systems on both sides; this was one of the model's original purposes.

In addition, however, the effects on force performance of certain changes in tactical doctrine can be measured. For example, alternative policies for the use of reserve units can be examined by varying the conditions under which reserves would be committed and reconstituted. Of equal interest is the representation of force aggressiveness and its influence on force performance. Varying degrees of aggressiveness can be simulated by causing systematic over- or underestimation of enemy strength in the estimates of the situation.

Force performance is also related to combat support capabilities and employment. Alternative policies of artillery and tac air employment can easily be studied, for example, and the model also dynamically represents the capabilities of combat engineers to construct barriers and the effects of these barriers on the course of the war.

Finally, force performance also depends on logistic support capabilities and policies, among which are the medical evacuation policy, personnel and materiel replacement rates, and maintenance capabilities. All of these can have a strong influence on the course and outcome of a campaign.

Thus for the first time the CEM provides an opportunity to explore by simulation the effects on combat success in a theater war of alternate combat organizations and weapons. In doing so, it gives the proper pre-eminent position to firepower but includes the influence of other combat functions more effectively than any previous model.

Operations Research in the Warsaw Pact Armed Forces

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The Warsaw Pact is a mutual defense pact between the Soviet Union and six countries. A seventh country--Albania--withdrew from the Pact in 1968. The Pact provides not only for mutual defense, but also allows Soviet Army units to be in the territory of the other countries. These countries are: Bulgaria, Czechoslovakia, East Germany, Hungary, Poland, and Romania. Since its signing in 1955, the Pact has been used to improve the military position and the diplomatic bargaining power of the Soviet Union in European and worldwide relations. Today the Warsaw Pact Armed Forces are a formidable array of men and weaponry--still strongly dominated by the Soviet Union.

The utilization of operations research in these Forces is varied--and it is growing. Specific details of applications and the exact extent of this utilization is not available in open literature as the Pact countries are careful to classify such information. A considerable amount of general data in this area is available, however, through open sources, and reasonably ~~valid conclusions can be~~ drawn from this. For example since 1963, numerous unclassified books and articles have been written by senior Soviet officers on military applications of operations research.[1-7] These were written specifically for other Soviet officers and are in a non-technical or slightly-technical style. Articles have also appeared from Czechoslovakia, Poland, and East Germany. In all of these publications the theme is to show the relevance of mathematical analysis to military operations.

In addition to these, finished analyses of the impact of technology on the Soviet military establishment are available,[8-10] and these address the impact of military OR applications. A wealth of material is also available in translated technical journals on the theory of and general applications of operations research as practiced in the Warsaw Pact countries.

The use of military operations research in the Pact had a slow beginning. It was not until the early 1960's that such use was uncovered. From that time until 1968, operations research activity spread and became more generally accepted in at least four countries of the Pact. From 1968 to present, such activity can best be characterized as experimentation with a growing variety of techniques, in both strategic and tactical applications. These activities have contributed to and continue to influence the technical revolution in the structure and operation of the Pact Forces.

This growing acceptance of OR techniques may be better understood in the context of several larger trends as follows: (a) the new Soviet leaders who replaced Khrushchev in 1964 were proponents of scientific management, (b) Soviet military leaders also reacted to Khrushchev's policies and other complicating factors with increased stress on improved decision making. The new political leaders also exerted pressure for greater efficiency in defense resource allocation. (c) Cybernetics became

widely accepted by the Soviets as the unifying theory for techniques for the control of complex organizations and (d) The Soviet reliance on central planning of its political-economic system creates special demands for analytical and reporting systems. Each of these factors will be discussed in turn.

Krushchev was ousted in 1964 by proponents of scientific management. They displayed their frustration with his management style by condemning him for subjectivism (or lack of objectivity), complacency, harebrained scheming, hasty conclusions, rash decisions, and actions based on wishful thinking, boasting and empty words. In 1965, the Chief of the General Staff, Marshal M. V. Zakharov presented the military's argument for improved decision making in an article titled, "An Urgent Demand of the Time: On Further Raising the Scientific Level of Leadership." During the 50's and 60's, the percentage of technically trained officers was also increasing significantly as well as the complexity of military operations. Such factors combined to generate a new science of military management in the Soviet Union. Additional inspiration came from the innovations in defense management in the United States and the Soviet interest in cybernetics as a general theory of management. The Soviet concept regarding cybernetics differs from that of the United States. In the US view, cybernetics is generally regarded more narrowly and is usually concerned with control of electro-mechanical systems. In Soviet Union, cybernetics is used as a unifying theoretical framework in which numerous disciplines (e.g. operations research, systems analysis, computer sciences, information science, control theory, behavioral and social sciences, etc., are drawn upon for the control of a wide variety of complex, dynamic systems. The Soviet acceptance of cybernetic theory is uniquely high. Soviet scholars have written the following: "the view of society as a complex cybernetic system with a multi-dimensional network of direct and feedback links and a mechanism of optimization, functioning towards a set goal, is increasingly gaining prestige as the main theoretical idea in the field of the technology of managing society". The use of cybernetics as the general theory of control and communication has been used by the Soviets in such diverse fields as command and control for large troop movements and in the elaborate computer network for central control of the Soviet economy which will be described later. Holloway,[10] an astute observer of Soviet political affairs points out the Soviets consider modern military advancement to be divided into three stages: the atomic, the missile-nuclear, and the cybernetic. In the latter stage, greater emphasis is expected on the development of improved troop and weapon control systems and advanced managerial techniques.

Consequently, the Soviet Union and other Warsaw Pact countries such as Czechoslovakia, and Poland now have far-ranging interests in the military applications of OR. The Soviets consider military OR as "the branch of military science which describes military operations in mathematical terms, and seeks a quantitative basis for decision making." The theoretical basis for these applications is often taken from theory developed in Western countries. Exceptions to this are mathematical optimization theory and probability theory, where the Soviets are doing some excellent theoretical work.

The primary tactical applications interest is in military war gaming and its associated analytical techniques. There is also interest in the following areas: (a) improving search and detection methods by math modeling or simulation, (b) determining routes for the transport of military personnel and supplies by the use of network theory, (c) finding the optimal or near-optimal distribution of weapons or personnel by the use of methematical programming techniques, (d) utilization of computer systems to assist the unit commander in decision making, (e) the use of mathematical techniques to analyze individual weapon characteristics, and (f) the use of queueing theory to improve air defense and ground combat capabilities.

The following specific examples are given as typical of the tactical applications being made a present in the Pact Armed Forces.

An East German writer has written[15] an interesting survey of game theory covering applications ranging from simple duel situations to international power struggles. The Warsaw Pact state-of-the-art in game theory has been judged by western observers to be equivalent to that of the west.

A 1972 Soviet military officer's journal[14] discussed the application of network planning to combat and training activities. The article described a short-cut tabular method for determining the critical path and slack times. The author claims network designs and calculations can be made in half the time required by conventional methods thereby yielding significant advantages for calculation of temporary networks under field conditions.

In an issue of the Soviet Military Herald,[17] an Engineer-Captain discussed the increasing use of modeling methods to aid troop commanders in decision making. As examples of such modeling applications he describes some rather basic approaches for modeling: (1) relative losses for opposing forces during an artillery battle, (2) combat losses of two sides during a series of strikes as predicted by Lanchester's system of equations and (3) a battle between tank and antitank weapons.

A Soviet text[16] points out that linear programming methods have been widely used for solution of certain types of military problems. As an example, the author uses the problem of determining how the allocation of monthly deliveries of aircraft between a combat mission and a supporting training mission can be made so as to achieve maximum military effectiveness.

In a 1969 Soviet book[18] on math modeling of tactical combat, the application of queueing theory to antitank defense was discussed. The problem was analyzed in depth with antitank weapons providing multiple "service" and with system failure being computed with the aid of a Markov process. The Soviets tend to apply queueing theory to more diverse applications than is done in Western countries.

In general, review of Pact OR publications reveals no new concepts or significant advances over western techniques. The difference lies in the extent to which implementation of such techniques receives high level support and the central role which cybernetics is assuming in military activities.

In addition, military OR should receive significant spinoff from equipment and techniques developed in support of the Soviet central economic planning system. One of the chief differences between Western and Soviet-type economies lies in the role assigned to the market. In the West the principal decisions of the economic system are made and carried out through the market mechanism. In the Soviet-type economies, the principal decisions are made by central planning rather than in the market and the market plans little or no role in the transmission of order or the collection of information. Thus the Soviet-type economies have to develop analytical methods and channels of communication and control which are not necessary in the West.

In the Soviet Union, Automated Management Systems have been in operation for industrial applications for about seven years. More recently, Automated Management Systems have been reported in East Germany, Poland, Czechoslovakia, and Romania. These systems function similarly to management information systems in the United States, but with an important difference.[11] Their systems are generally based on the dynamics of the firm, rather than on a series of transactions or operations. This is due to the nature of Socialist business enterprise, and it requires software based more on dynamic system modeling than is the case in the United States. The Socialist enterprise system is also amenable to a hierarchy of management systems to enhance overall planning and control. The lightly competitive nature of Socialist enterprise also allows developed software to be shared more freely between individual organizations. These factors make it feasible for the Soviets to design large, multilevel, integrated control systems. There is, in fact, an ambitious plan to simulate the economy of the entire Soviet Union.[12] Eight hundred regional data processing centers are to link approximately 40,000 manufacturing plants, retail outlets, finance and service centers, and government agencies into a management information network. This is known as the All Union Management System. Regional centers would be linked by a telecommunications network, and data banks in each regional office would contain information on the area's industrial and agricultural production, transportation facilities, labor population, and growth capacity. Such a system would be a real-time system, encompassing all aspects of Soviet economic life. The other Pact countries, particularly Poland, Hungary, and Czechoslovakia are planning similar projects.

To help provide the computer for this and other computer needs, the RYAD program was implemented. The Warsaw Pact countries are building for common use a third generation computer with six model variations. These computer systems are designed to accept IBM-360 programs, which will result in a tremendous saving in software development costs. Each country has specific assignments to design and build components or items of equipment for the RYAD systems. The Soviet Union is supervising the project and is independently working on all phases of the program so as to have a full RYAD manufacturing capability.

The point of all this is to show the scope of intended computer usage to plan and control. The capability is thus present to develop advanced military command and control systems. Such systems would be based on a hierarchy of computers with an interconnecting data transmission system. Hierarchy here means a multi-level system with the higher level device controlling more than one lower level device. Initially, the lowest level devices are placed into operation. Higher level devices with the ability to monitor and control are then added. This operation is repeated until all devices are under one central control. The primary aim of such a system would be to increase the decision maker's capability by providing more information and by providing this information more quickly. The decision maker can then make, implement, and verify implementation of decisions in a shorter span of time. Other benefits would be improved control of the movement of men and weapons, improved logistics flow, and improved integration of operating and service functions.

The movement toward technology in the armed forces has been greatest in the Soviet Union. Of particular import is the trend to replace veteran ranking Soviet marshals and generals by men skilled in advanced scientific and engineering fields.[13] The trend is also apparent in lower ranking officers, where the proportion of engineers is much higher than in the past, and where commander-engineers achieve faster promotions. The former chief of the General Staff, Marshal Zakharov, stated that all officers need not be engineers but that every commander should have a deep knowledge of physics, mathematics, chemistry, electronics, and cybernetics. He further commented that "it is very important to be able to make wide use of computers and other equipment which will make it possible in very short periods of time to make correct assessments of the situation and to take bold and well-founded decisions." At present in the Pact Armed Forces there is some resistance by officers to the changes in operating procedures entailed by the increase in automation. Some officers apparently feel that automation will pre-empt their authority.

In summary, OR was slow to gain acceptance in the Warsaw Pact until the 1960's at which time a number of factors combined to increase the receptivity for OR methods. The OR techniques utilized in the Pact have generally been drawn from the West. The most significant difference lies in the extent to which cybernetic theory (to include OR techniques) has been accepted as a unifying theory for the management of the Soviet political and economic system and for the improvement of the defense forces. A sampling of the Soviet literature indicates they may well consider the third step of modern military development to be the cybernetic stage. If so, we can expect significant effort in the development of equipment along with the necessary theory and software for military operations research with emphasis on techniques for the direction or control of large military systems.

In the future we will see in the Pact Armed Forces:

- Advances in central planning methods, which will utilize large scale simulation and computer networks.

- Simulation and other OR techniques will be used specifically to aid in the decision to develop weapons systems.

- On-line operating systems of interconnected computers for command and control.

- A widening of OR experience in the smaller countries of the Pact as more high-speed computers become available.

- A greater acceptance of OR techniques to aid in tactical operations as more officers become trained in the use of such methods.

Operations Research has found its place in the Warsaw Pact Armed Forces, and its impact is just now beginning to be felt.

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THE IMPACT OF BATTLEFIELD TERRAIN ON DIRECT-FIRE ANTITANK WEAPON PERFORMANCE

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INTRODUCTION

Rapidly evolving technology has brought into reality the possibility of first-round hits and kills of armored vehicles at ranges in excess of 3000 meters, even under poor meteorological conditions. Because this is a new operational envelope for direct-fire ground-to-ground weapon systems, and because procurement decisions are complicated by questions involving the number of complex, expensive missile systems required to meet future threats, it is important to have an understanding of the limitations imposed upon such systems by the battlefield environment, including terrain, weather, and tactical situation.

Breakthroughs in missile seeker design now permit acquisition of long-range targets, with lock-on achieved through a variety of terminal homing techniques, ranging from active guidance (exemplified by use of laser-designators to "paint" targets with encoded radiation) to totally passive acquisition, as used in the class of missile systems which relies on forward looking infrared (or FLIR) detection systems. Such systems are capable of "seeing through" battlefield haze and smoke by taking advantage of IR absorption windows in the 8-14 micron wavelength band.

This new technological capability leads one to the conclusion that the primary limitation on the performance of the new missile systems is likely to be obstructions blocking the weapon-target line-of-sight (LOS), such as buildings, vegetation, and the earth's surface itself. Although weather and smoke are reduced as problems as far as the missile seeker is concerned, they will still complicate the antitank crew's attempts to acquire targets visually. Therefore, a brief examination of probable weather conditions in several theaters of operation is instructive.

WEATHER

Figures 1-4 give the probability of atmospheric visibility being greater than or equal to a selected range as a function of the season of the year for Frankfurt and Fulda, West Germany, Seoul, Korea, and Bangkok, Thailand. It can be seen that the chances of having visibility

exceeding that required for visual target acquisition are relatively high throughout much of the year in each area. These data, however, reflect peacetime weather conditions, and can be expected to deteriorate during periods of artillery fire and massive armored movement, due to dust and burning vegetation and targets, as well as from tactical smoke employed by artillery, tanks, armored personnel carriers, and helicopters.

The change in visibility for an obscured battlefield environment near Frankfurt is estimated in Figure 5. The lower curve predicts the visibility probabilities in an environment in which a haze with a known atmospheric attenuation coefficient ($\sigma = 0.5\ KM^{-1}$) has been inserted between the observer and the target. Although not an insurmountable obstacle to an observer with electronic and optical aids, this presents a challenging target acquistion environment for an observer with an unaided eye.

TERRAIN AND LINE-OF-SIGHT

Several field tests concerning observer capability to detect both fixed and moving targets have been conducted, both in the U.S. and in Europe. One of the most comprehensive tests of this type is currently being completed at Hunter Liggett Military Reservation, California. TETAM - Tactacial Effectiveness Testing of Antitank Missiles - has obtained field information on distributions of line-of-sight, target exposure and acquisition, weapon system reaction time, and counter-measure techniques.

HELAST, a tank - antitank test conducted at Ft. Knox by the Human Engineering Laboratories, Aberdeen Proving Ground, has provided insights into the target "flicker" phenomenon - the tendency for armored targets approaching a defended objective area to alternately appear and disappear from view with a mean exposure time on the order of four seconds and an expected masked time of nearly three seconds. Although these times are smaller than corresponding times recorded in some other field tests and those predicted in simulations utilizing digitized topography, they are the results of carefully measured field experiment, and point out the possible difficulties encountered when attempting to track targets in an environment with trees scattered either in the vicinity of the observer or the target. This effect is analogous to the moire effect visible when the observer views a scene through either a fine-toothed comb or a picket fence. If the mean time between successive exposures is small, the observer may have little difficulty tracking a target. However, the implications are not clear-cut in the case of some missile seeker mechanisms, and may depend upon false target rejection logic and the type of command link used.

Digitized terrain has been used to characterize the variety of combat situations in which a sophisticated antitank system must function. Research in this area performed at both the Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, MD and by personnel of the Waterways Experiment Station, Vicksburg, MS appears to be in fairly close agreement with field test results, once differences in measurement technique and geographic location are accounted for. This outcome is indeed encouraging, since it may be possible to do more extensive sampling in the long run using digitized terrain as the investigative tool than is possible with the limited number of suitable test areas available and the expense required for a well-documented on-site experiment of this type. Another advantage of the digitized terrain simulation lies in the ability to use this technique to analyze areas which are not easily accessible, be it for political or other reasons.

Tools required for such a simulation include digitized terrain, a rapid, but accurate line-of-sight algorithm and a valid tactical scenario. The digitized topography must resolve vegetation, terrain and cultural features capable of masking targets the size of a tank or APC. This necessitates either high quality stereo pairs of the area of interest or the contour maps generated from this photography. Ideally, the map should posess vertical information at least down to the order of the observer and target heights being analyzed, that is two meters or less.

Grid size or spacing is also an important facet of the analysis. A uniform square grid is utilized to ease computer programming, memory, and time requirements. Elevation data are stored in a specified order in the computer memory, thus avoiding the need to store x-y information in addition to the elevation data. Figure 6 presents a statistical "feel" for the effect of changing grid size in a line-of-sight (LOS) analysis. Here, LOS probability vs. range from random observer positions has been computed for grid spacings of ten, twenty, and fifty meters. Adequate grid size is obviously related to the surface roughness or expected inter-hill distances in the region in question. Spacings of 100 meters are generally an upper bound for ground-to-ground analyses in rolling terrain, and the smaller the grid spacing, the better the fidelity with which such a model can replicate test results and establish validity.

Figure 7 represents an area West of Aberdeen Proving Ground for which special one meter contour maps are available. Superimposed on the topographic map are a tactical overlay and an LOS masking overlay for an observer position designated by the small triangle. This overlay is generated by a program which accepts as input a digitized terrain grid and a set of observer coordinates and produces a masking overlay to the desired scale on a Calcomp plotter. Clear regions on the overlay indicate areas in which the observer has complete surveillance of the ground and any targets upon it. Regions covered by characters indicate areas in which targets would be in at least partial defilade. The amount of defilade is reflected in the encoding scheme.

The technique just described has been used to estimate distributions of target visible path segment length, weapon-target opening range, and vantage point line-of-sight probability. This information has been documented for four regions in AMSAA Technical Memorandum No. 158. The technique will be used in the future in an attempt to duplicate in a simulation, data obtained in the TETAM and HELAST field tests.

Figure 8 is a histogram indicating the distribution of weapon-target opening ranges combined for the four tactical situations analyzed in TM 158. Opening range is defined as the distance from an observer to any point on an attacker approach route where a target comes into a full view of the observer. The mean opening range for the four areas is about 2200 meters and the average number of visible segments from the start of the appraoch to the objective varies between 3.0 and 3.4 per path.

Figure 9 displays the distribution of visible path segment lengths, again for the four regions combined. The mean segment length is 361 meters and corresponds to an average exposure time of forty-three seconds for a target speed of thirty kilometers per hour. This suggests that minimizing the reaction time of a sophisticated antitank weapon system may be much more fruitful than striving to achieve maximum effective ranges in excess of three kilometers. Seventy-eight percent of the target exposures occurred at ranges less than 3000 meters. It also provides a strong argument for tailoring antitank forces so that the long-range class of antitank weapons is not deployed in areas in which long lines-of-sight are non-existent. Organizing the long-range tank killer force to be organic at battalion level or above could reduce procurement costs for the more expensive long-range systems and free funds for a larger buy on intermediate and/or short range antitank weapons.

Table 1 summarizes the statistics derived for each region. The data are of interest in that they indicate a positive correlation between the mean opening range for the region and its mean visible path length -- the mean segment length being roughly equal to the mean range times 0.2 for three of the four areas. This information can be restated in terms of the probable lengths of time a moving target is visible and available for a fire mission before breaking line-of-sight. Figure 10 shows the probability of at least an x minute exposure time for target speeds of ten, twenty, and thirty kilometers per hour. These data have been generated both independently of range and for particular range bands. Little variation in results is observed, indicating for these four tactical situations, at least, there is no strong correlation between target duration time and range. Figure 11 presents information similar to the previous figure. In this case, however, the target speed is held constant at thirty kilometers per hour, and the variation of the resultant duration time probabilities is shown for the four situations. Although there is some variation in results among areas, it is not as great as would perhaps be expected, in view of the differences in terrain over which the simulation was played.

Figures 12, 13, and 14 present 3-D perspective plots of the digitized terrain samples used in the evaluation (with 5:1 vertical exaggeration). It can be observed that while all three regions might be typified as gently rolling terrain, the Fritzlar "A" scenario contains a broad river valley which tends to allow long-range lines-of-sight, and once established, several of these intervisibilities are maintained over long periods of time. Even so, the curve for the region with the best intervisibility is not vastly different than that obtained for the region with the closest terrain (Fritzlar "B"). Thus, these curves may do a fair job of defining the reaction time envelope in which an antitank weapon will have to function in a European type environment.

DEFENSIVE OBSERVATION REQUIREMENTS AND PATH COHERENCE LENGTH

The procedure previously outlined is currently being modified to examine the number of forward observers required to provide maximum surveillance over a battalion sector. Figure 15 illustrates a variant of the output available from the LOS masking program. Here, the coverage from two observer positions has been combined to form a composite overlay. Open areas are completely visible to both observers, while other areas are either in partial or full defilade to both or in the remaining cross-product intervisibility space (i.e., exposed to one, and in partial defilade to the other, etc.).

Further work is currently in progress to determine probability distributions for multiple acquisitions of one target by two or more observers and vice versa in several of the digitized areas now available. However, investigations of this nature have already been accomplished using the TETAM data by personnel at Waterways Experiment Station and will likely be discussed elsewhere during this symposium.

NATICK LANDFORM CLASSIFICATION SYSTEM

One question which frequently occurs in studies involving the environmental characteristics of a region is: "How well does the region examined typify the whole theater of operation?" Another question often asked is: "Given that I know the effects of terrain on the outcome of military operations in one sector of the earth's surface, can I either assume that the outcome will not materially change if I move the operation to another similar sector, or if the new region is not similar, can I use the results of the first analysis in any way to predict the outcome of operations in the second?" Although to answer these questions is a formidible task in total, there have been several attempts to categorize terrain from both intervisibility and mobility points of view, and to categorize regions of the world according to climatological factors. One such effort

produced for AMSAA by the Earth Sciences Laboratory, U.S. Army Natick Laboratories, classified terrain according to surface roughness. Map measurements are used to describe landform compartments according to their maximum local relief, modal local relief, and the number of positive features per mile. Combined, they present a sinusoidal statistical picture of terrain whose variation lies in the amplitude and period of oscillation of the ground.

Table 2 provides a breakdown of the descriptor class intervals used in the classification. Figure 16 shows the terrain classification overlay this system produced for West Germany. Although this system is not detailed enough to expect a one-to-one correspondence of the surface geometry in two regions with identical landform classifiers, it provides a manageable classification set for purposes of comparing terrains with respect to intervisibility and hill slope. In combination with other systems which describe soil, climatological and vegetation properties, it may lead to a breakthrough in a quantified environmental description of the large areas required for systems analysis and war gaming of large unit operations.

CONCLUSION

Recent reductions in military expenditures, coupled with a desire to get the most utility out of Army antitank weapon systems, have kindled a widespread interest in determining the benefits of tailoring tank killer forces to match both the threat and the operational environment. Such an effort might prevent weapons with effective ranges of several kilometers from over-employment in regions where either the probability of line-of-sight to a long range target is low, or the reaction time of the antitank system, given a line-of-sight, is large compared to the target "duration time," i.e., the time span over which the moving target remains visible.

Digitized topography has been utilized to estimate distributions of tank/antitank opening ranges of engagement and target duration time for several regions. The method may be expanded to predict the optimum number of antitank weapons of different classes necessary to defeat an armored attack as a function of force size and terrain type.

Efforts are underway at AMSAA to check the validity of the Natick classification system when used to predict intervisibility characteristics such as LOS probabilities and distributions of visible path lengths on the battlefield. Progress has been slow to date, due to a shortage of the detailed digitized topography required for such an investigation. Hopefully, support from the Defense Mapping Agency will at some future point in time, help create the data bank required for such an undertaking.

In order to further establish the credibility of this statistical environmental description, more comparison between analytic predictions and field tests like TETAM, HELAST, and MASSTER will be required. To this end, efforts are in progress at AMSAA and elsewhere to obtain the field test coordinate information and digitized topography needed for a thorough comparison of the two techniques. If the experimental and simulation results prove compatible, systems analysts and decision makers in the defense community will have a valuable set of tools at hand to make intelligent decisions concerning the performance characteristics and force structuring of future weapon systems.

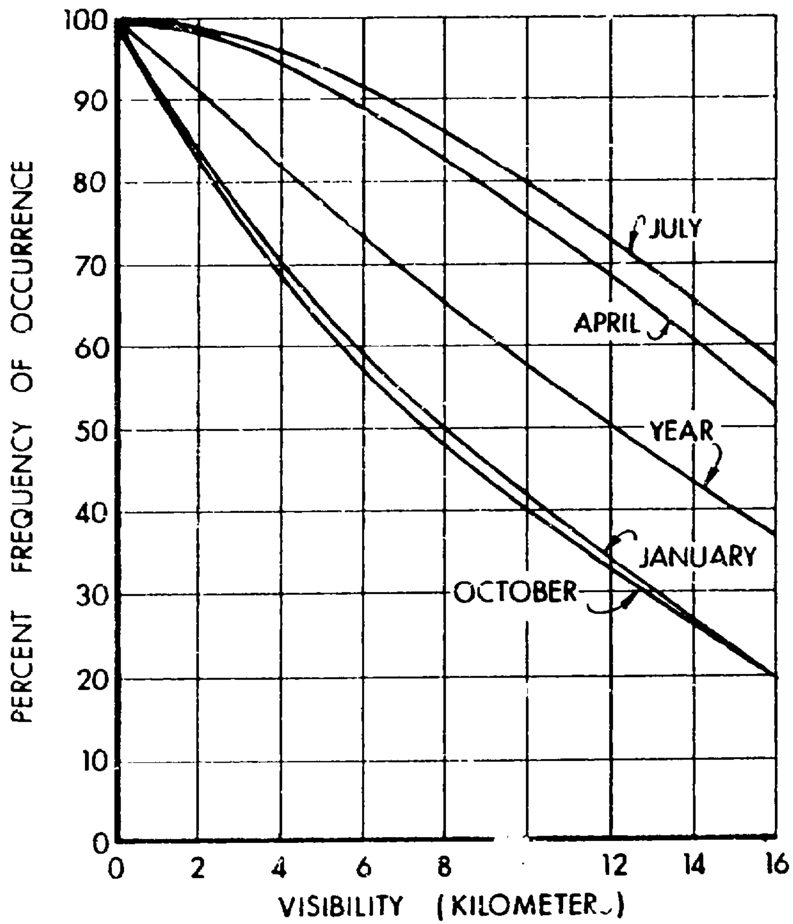

Figure 1. Percent Frequency of Occurrence
vs
Visibility (Kilometers)
Frankfurt, Germany

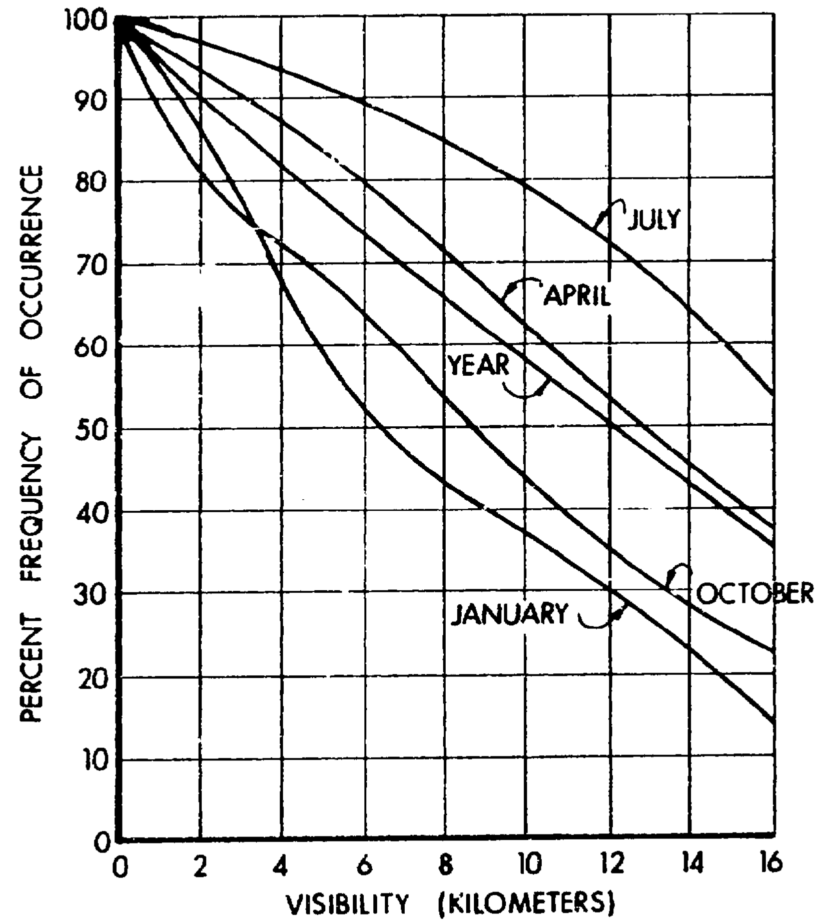

Figure 2. Percent Frequency of Occurrence
vs
Visibility (Kilometers)
Fulda, Germany

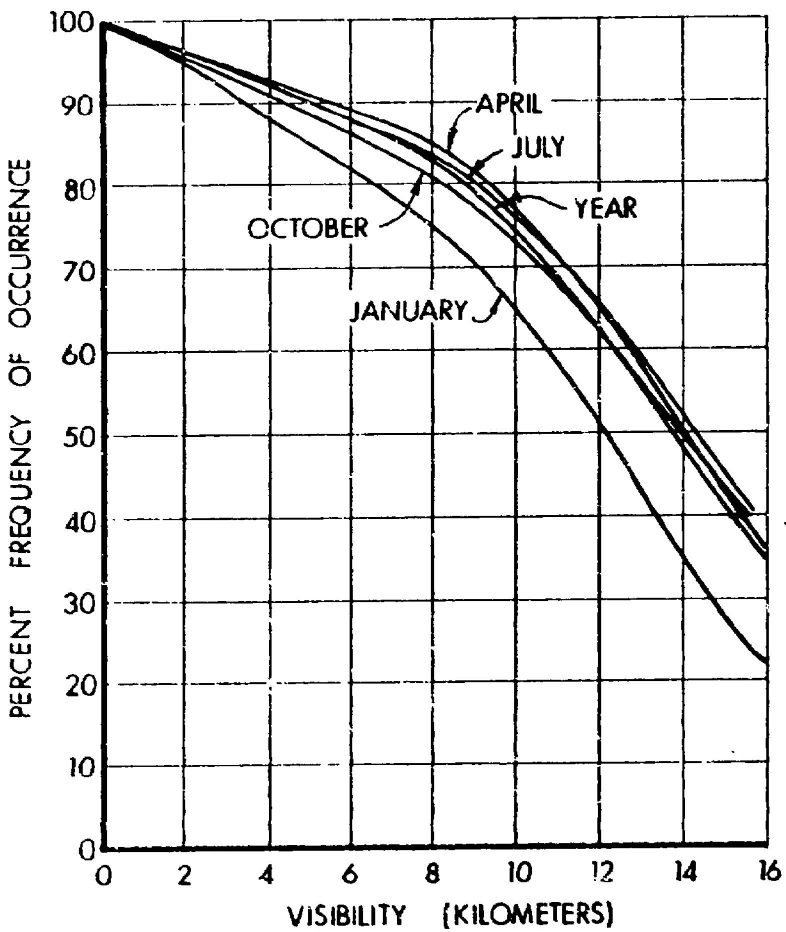

Figure 3. Percent Frequency of Occurrence
vs
Visibility (Kilometers)
Seoul, Korea

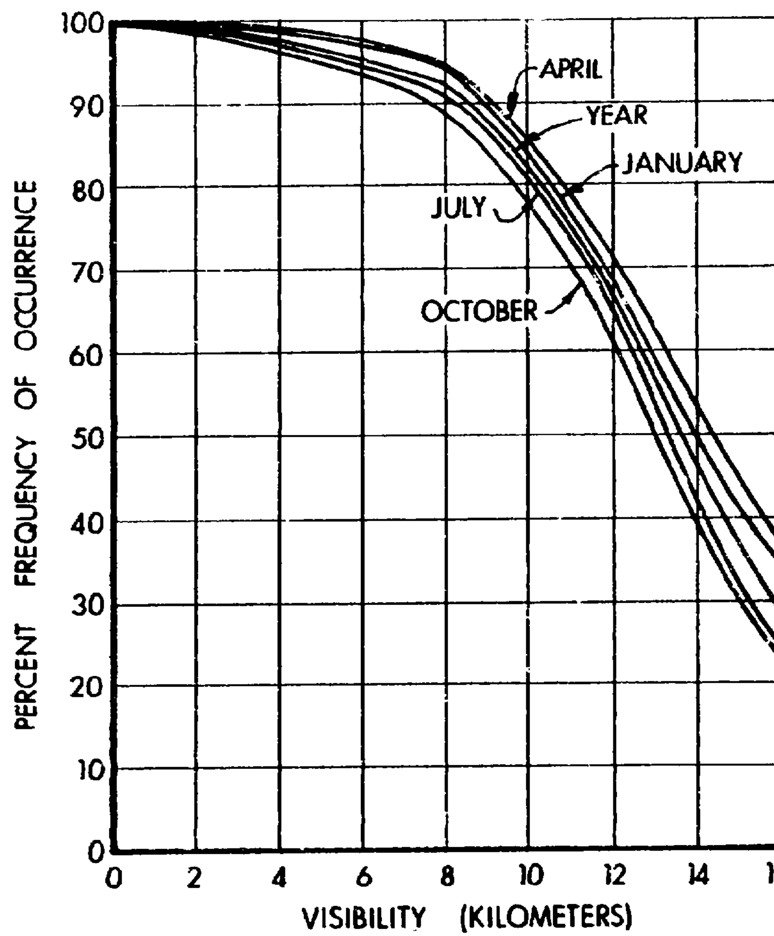

Figure 4. Percent Frequency of Occurrence
vs
Visibility (Kilometers)
Saigon, Vietnam

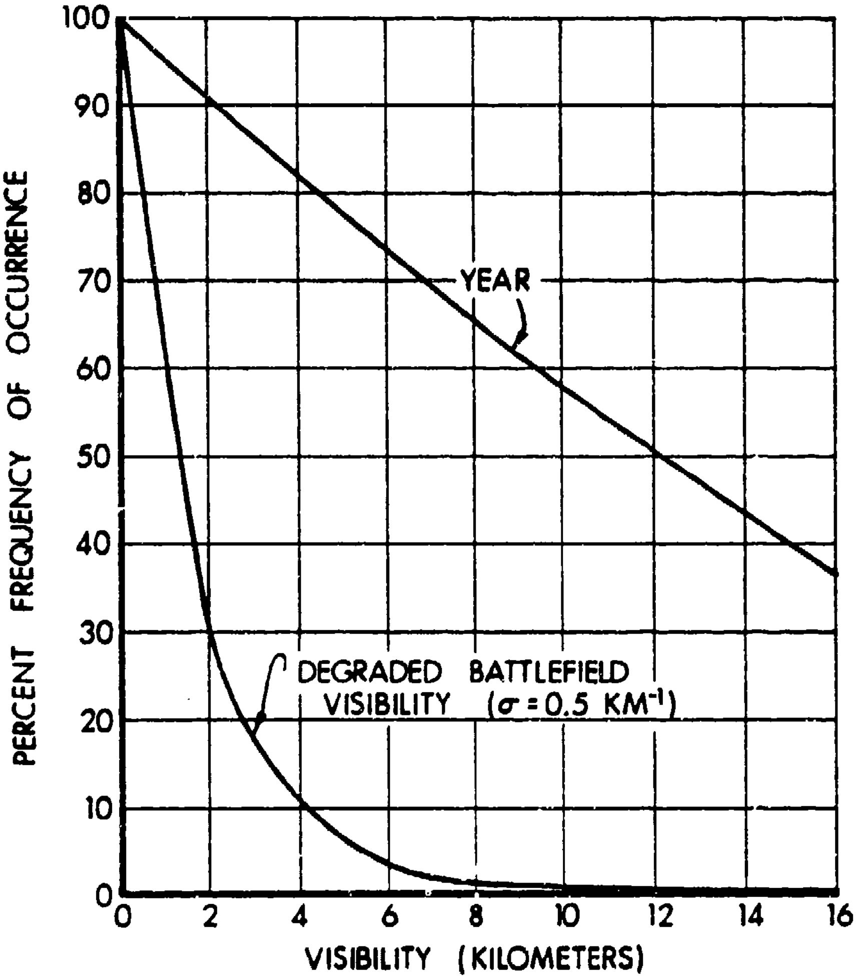

Figure 5. Percent Frequency of Occurrence vs Degraded Visibility (Kilometers) Frankfurt, Germany

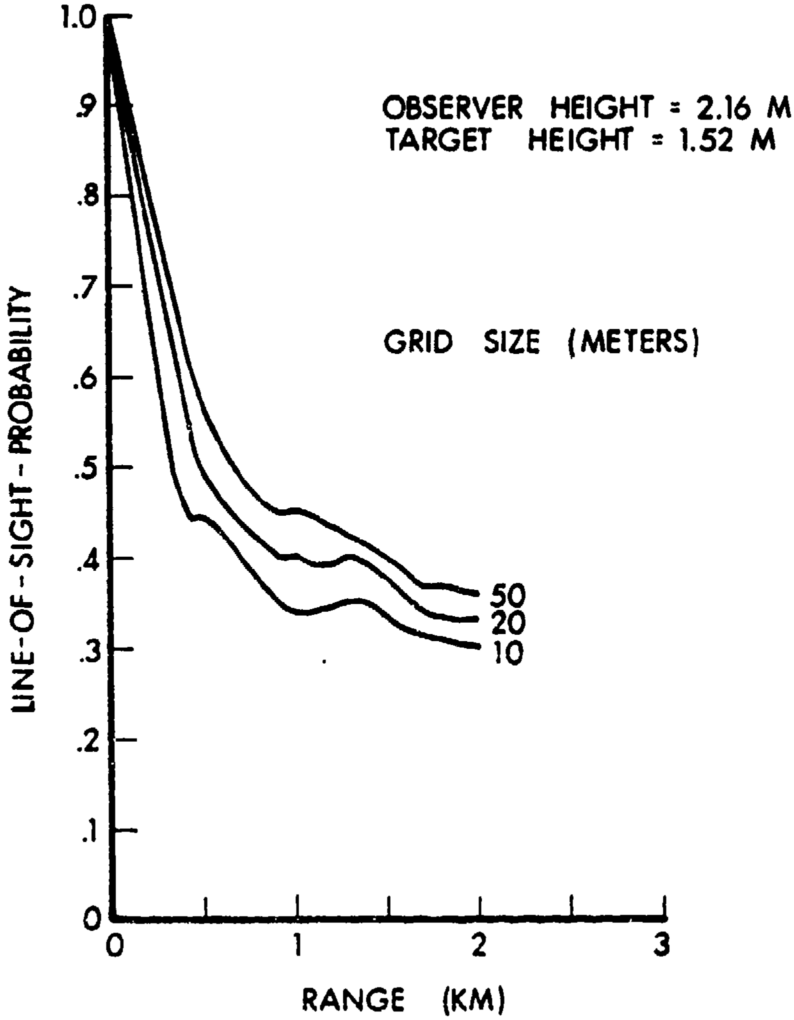

Figure 6. LOS Probability vs. Range. (Random Location, No Vegetation)

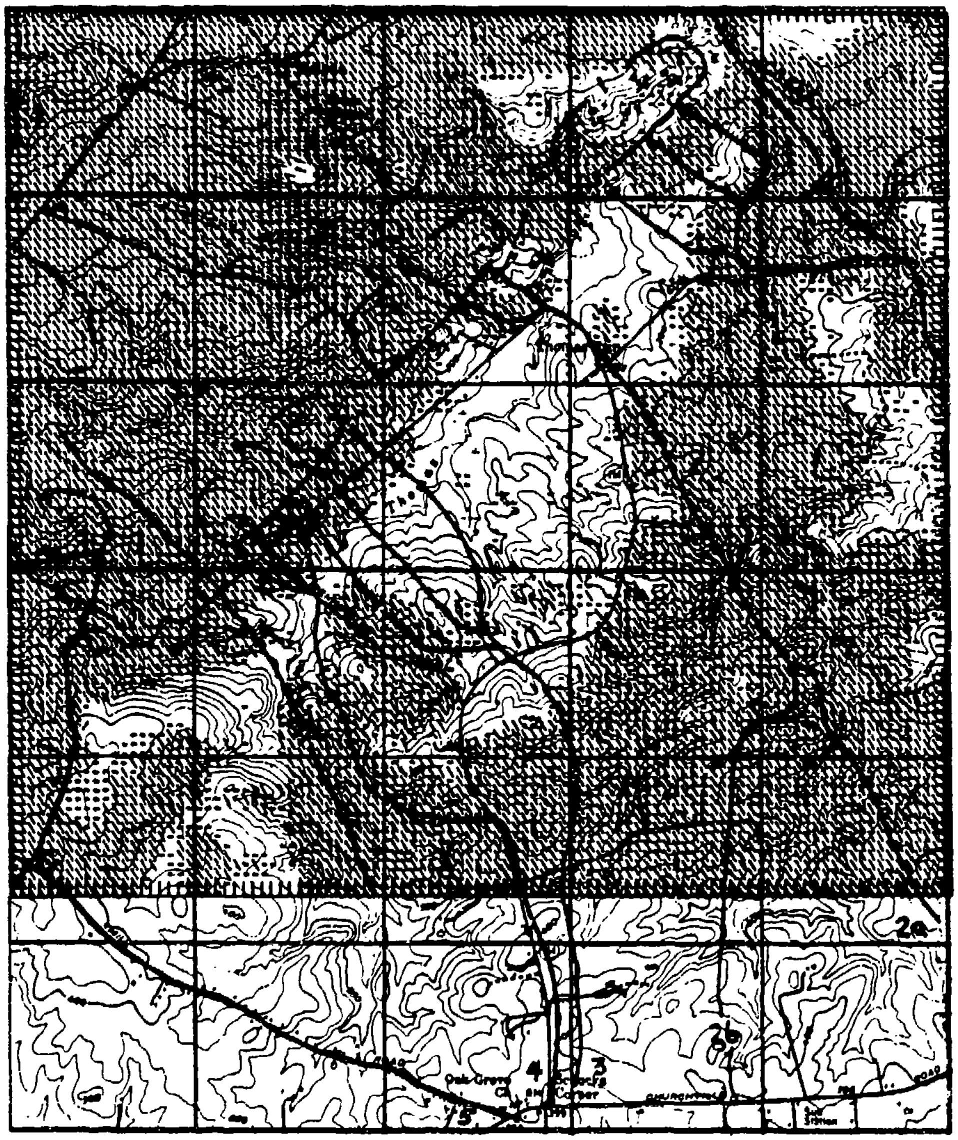

Figure 7. Map of Aberdeen Region, Showing Tactical Situation.

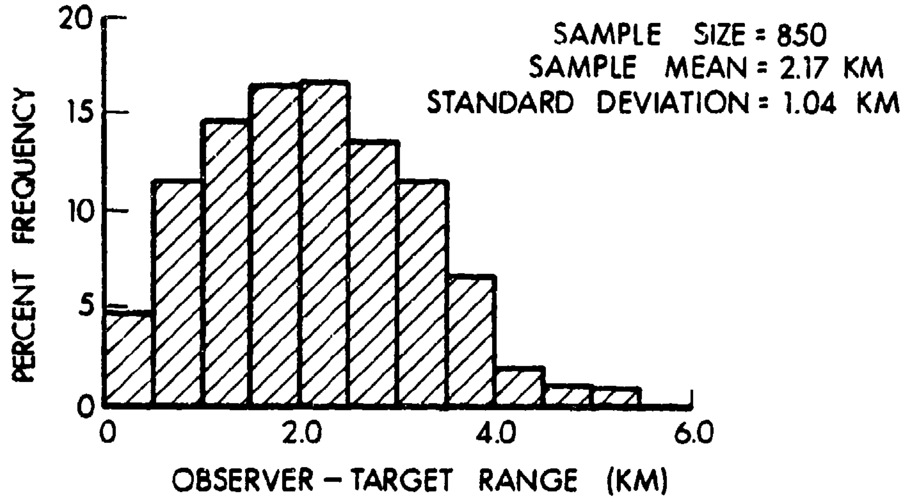

Figure 8. Distribution of Observer – Target Opening Ranges, Averaged Over Fritzlar "A", "B", Melsungen, and Aberdeen.

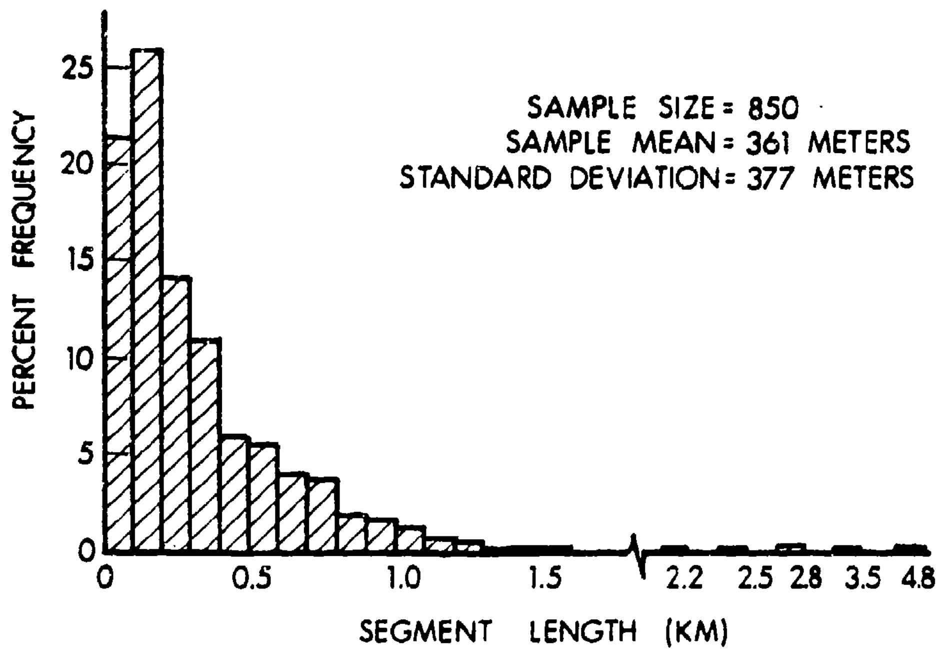

Figure 9. Distribution of Visible Segment Lengths, Averaged Over Fritzlar "A", "B", Melsungen and Aberdeen.

REGION	RANGE (KM)			SEGMENT LENGTH (M)		
	M	S	N	M	S	N
FRITZLAR "A"	2.89	1.33	132	486	670	132
FRITZLAR "M"	2.12	1.07	270	366	338	270
ABERDEEN	2.02	0.84	318	350	275	318
FRITZLAR "B"	1.94	1.09	130	253	227	130
AVERAGE	2.17*	1.04**	850	361*	377**	850

M = SAMPLE MEAN

S = STANDARD DEVIATION

N = SAMPLE SIZE

* WEIGHTED MEAN

** DERIVED FROM POOLED VARIANCE

Table 1. Statistics: Fritzlar "A", "B", Melsungen and Aberdeen.

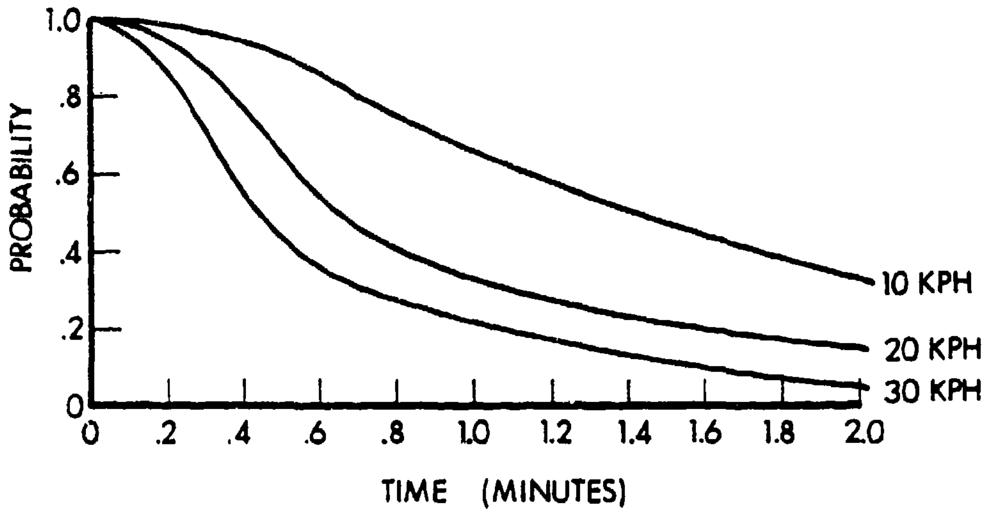

Figure 10. Probability of at Least X Minutes Duration Time for Target Speeds of 10, 20, and 30 KPH (All Ranges)

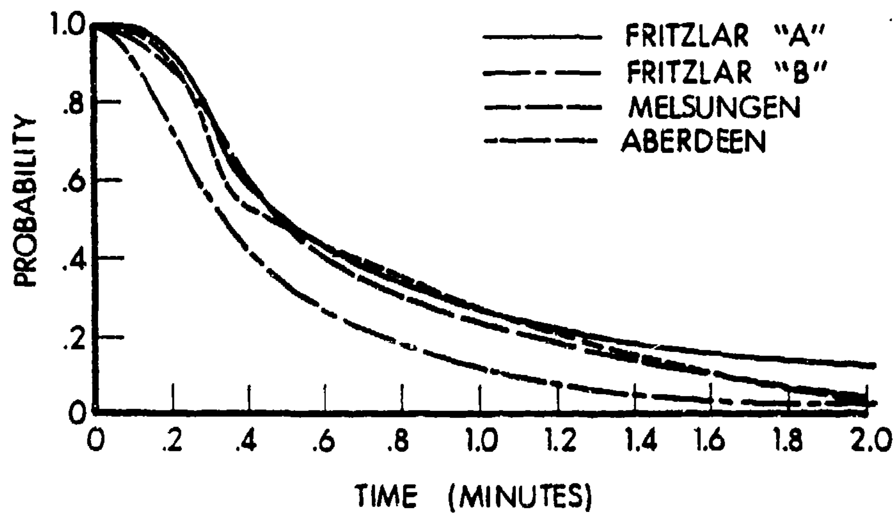

Figure 11. Probability of at Least X Minutes Duration Time for Target Speed of 30 KPH.

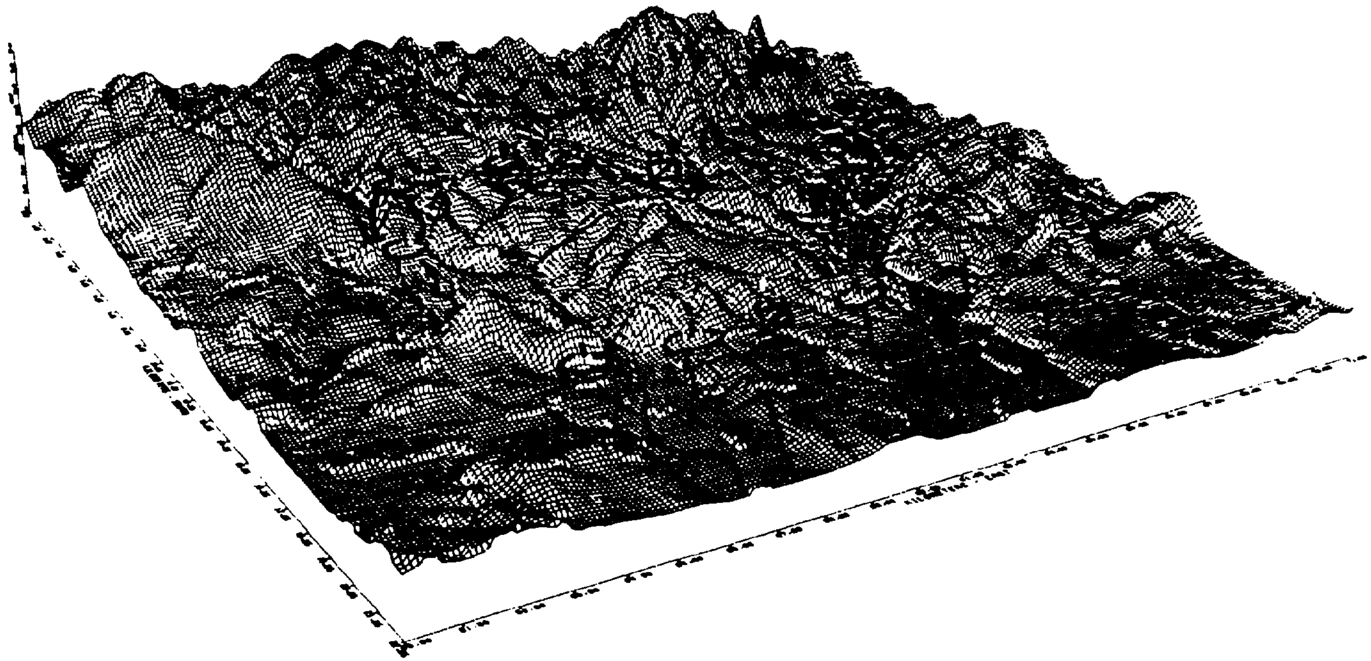

Figure 12. 3-D Plot of Fritzlar "A" and "B".

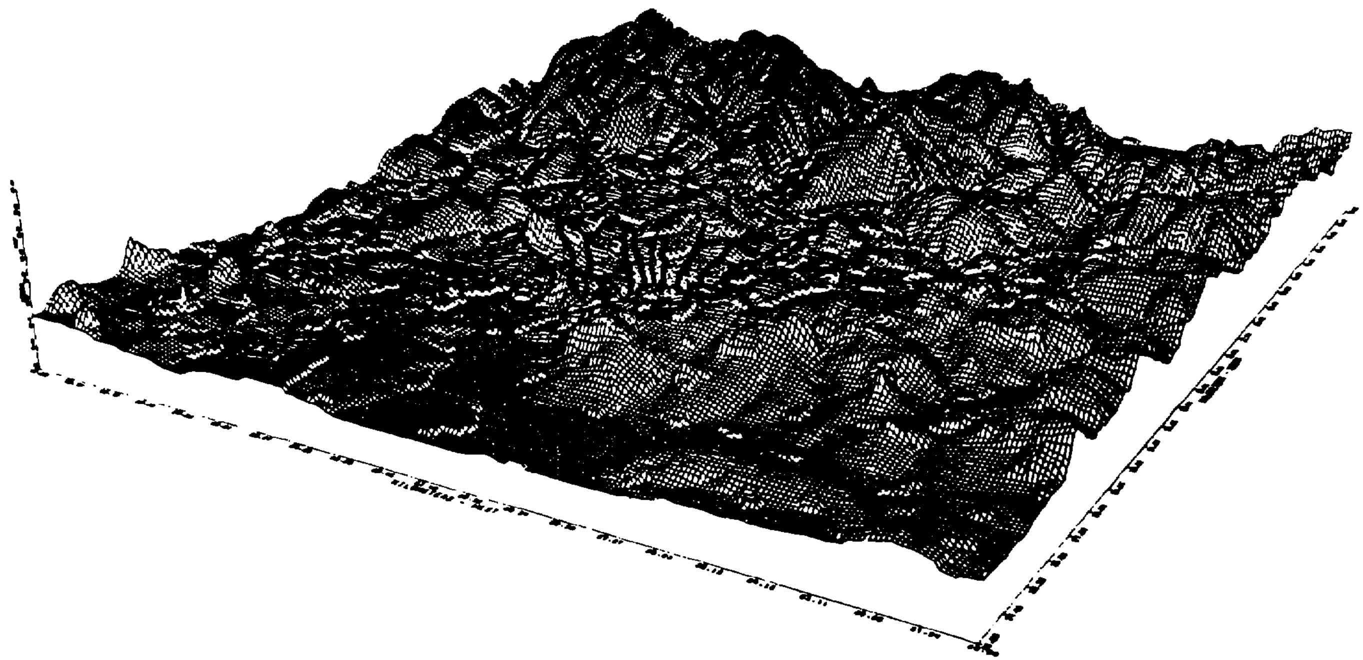

Figure 13. 3-D Plot of Fritzlar Melsungen.

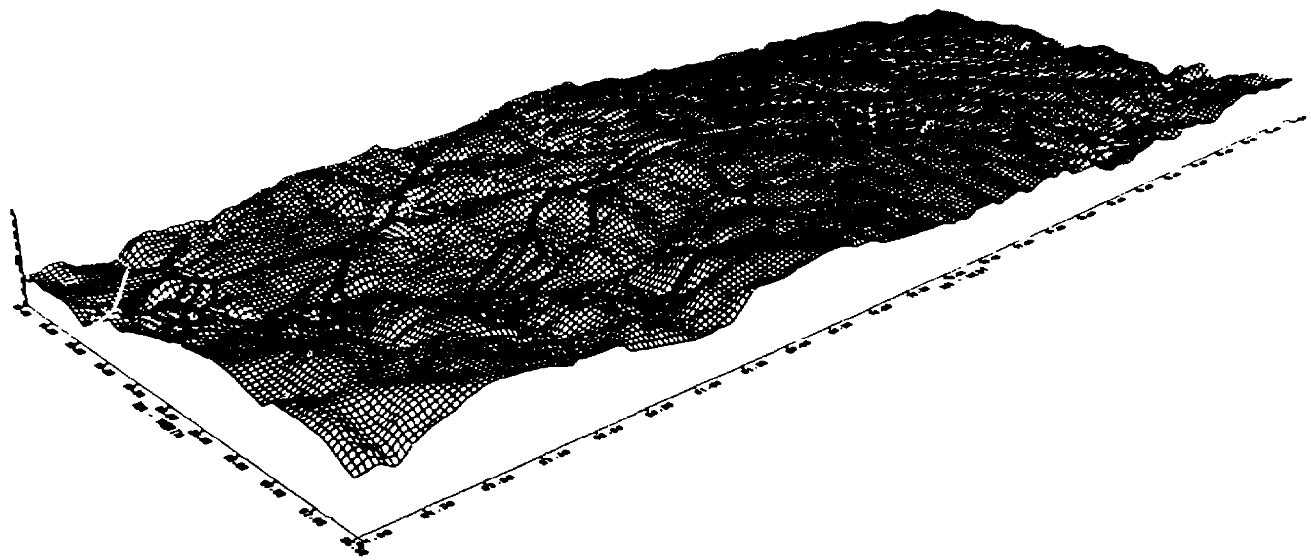

Figure 14. 3-D Plot of Aberdeen.

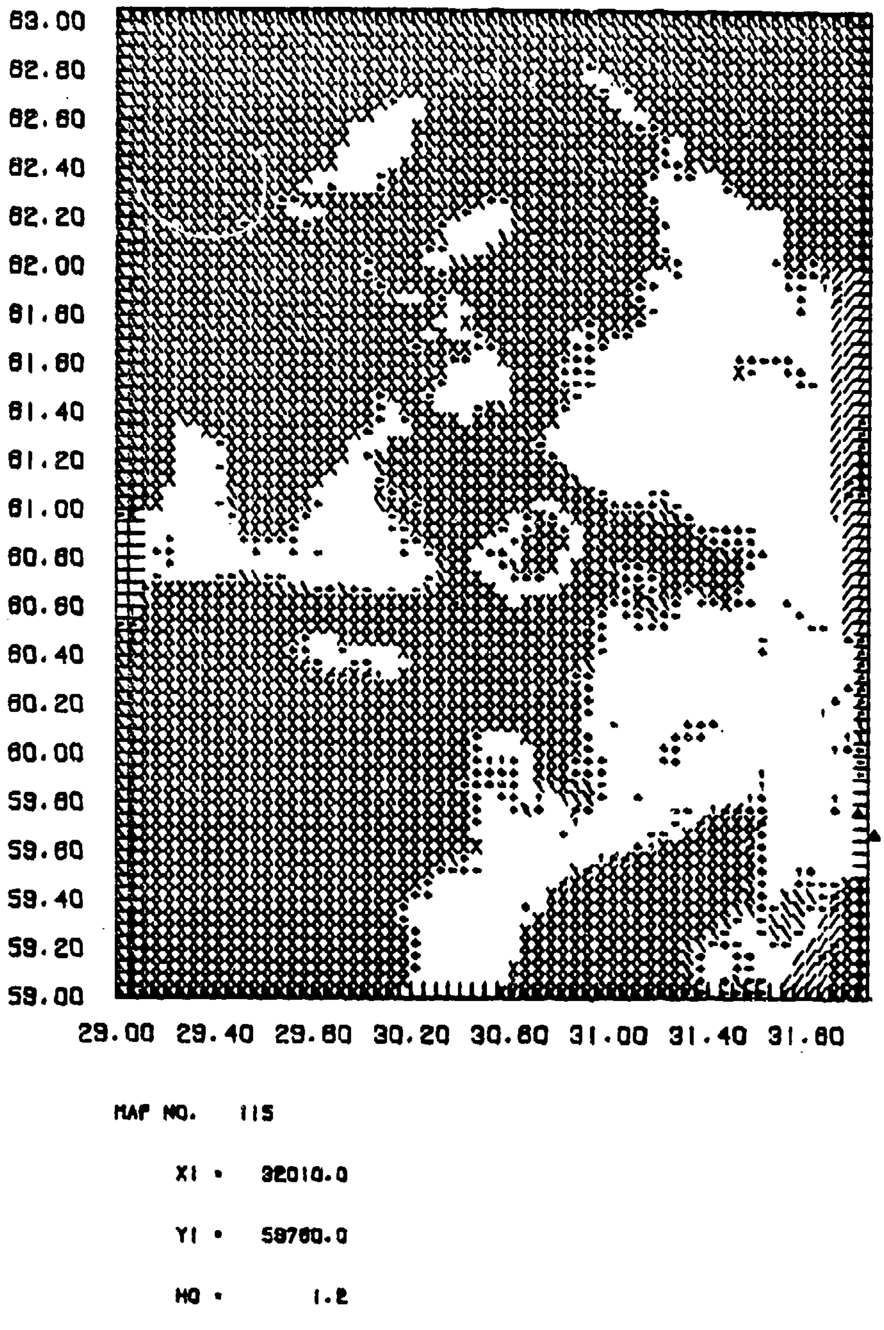

Figure 15. Composite Masking Overlay for Two Observers.

TABLE 2: NATICK LANDFORM CLASSIFICATION CODE

I. Maximum Local Relief

1. 0-10 meters
2. > 10-30
3. > 30-50
4. > 50-100
5. >100-300
6. over 300

II. Modal Local Relief

A. 0-10 meters

B. > 10-20

C. > 20-30

D. > 30-50

E. > 50-75

F. > 75-100

G. >100-125

H. >125-150

I. >150-175

J. >175-200

K. over 200

III. Positive Features per Mile

a. 0.5

b. >0.5-1.0

c. >1.0-1.5

d. >1.5-2.0

e. >2.0-2.5

f. >over 2.5

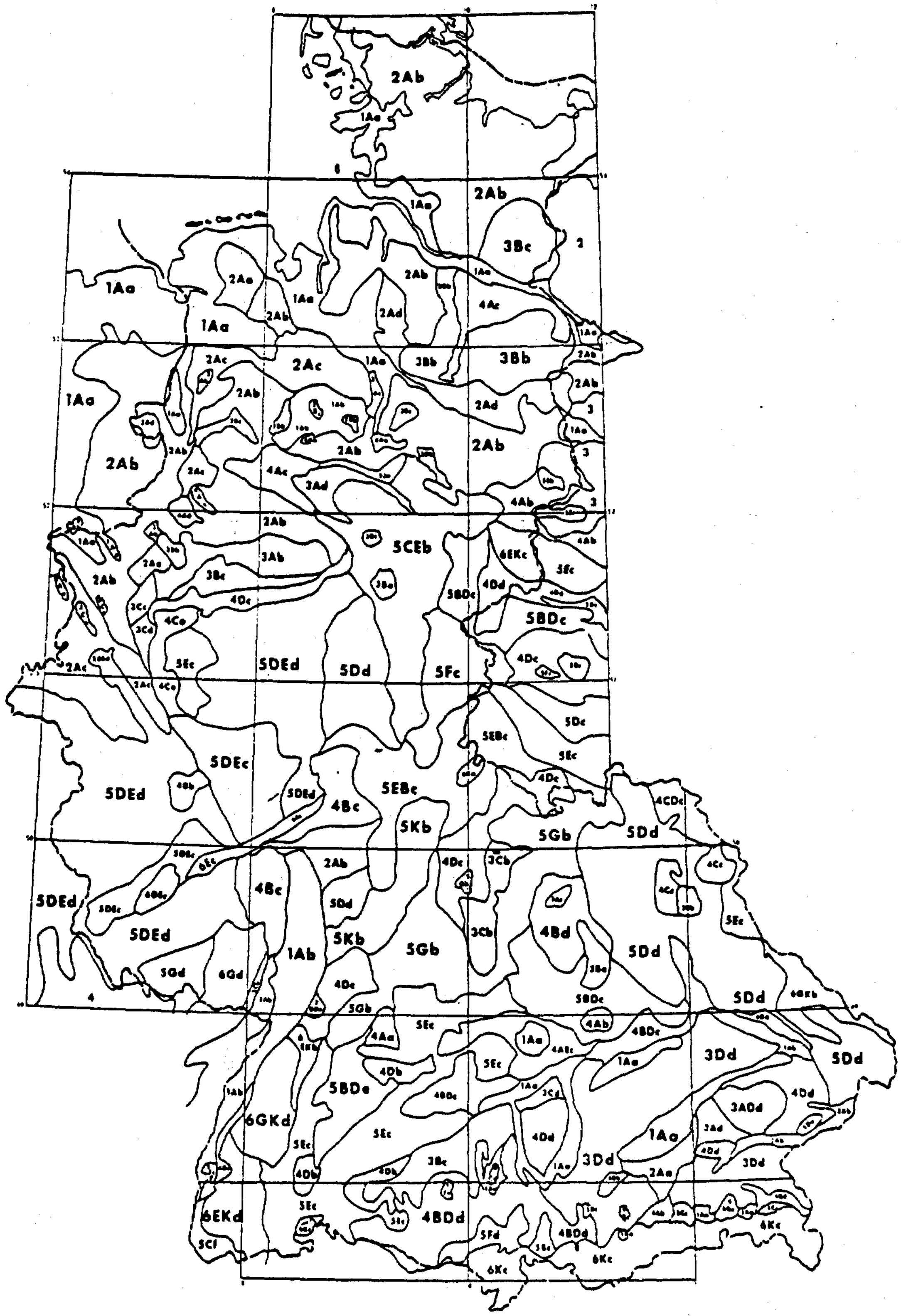

Figure 16. Terrain Classification Overlay. Federal Republic of Germany.

ON GROUND TO GROUND INTERVISIBILITY

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ABSTRACT

As a part of the Army's Tactical Effectiveness Testing of Antitank Missiles (TETAM) program, extensive field work was conducted in 1972 on determination of existence of line of sight. This work was conducted on twelve sites in Germany, two at Hunter Liggett Military Reservation and two at Ft Lewis, Washington. The objective was to determine that portion of each of several realistic armor attack routes which was intervisible with given defensive positions. A somewhat surprising result was the variability from site to site within a seemingly homogeneous area. Analysis of the tremendous volume of data generated continues.

I. Introduction

In the Spring of 1972 the Combat Developments Experimentation Command conducted an intervisibility experiment in Germany. This European based experiment, designated Phase IE: TETAM, was a part of the Army's Tactical Effectiveness Testing of Antitank Missiles program. The data collected in Phase IE provided a means:

To quantitatively ascertain the existent intervisibility patterns of the selected sites.

To determine if a functional similarity existed between FRG terrain and terrain in CONUS where further experimentation would be conducted.

To obtain data affecting target acquisition by ATM systems and tank crews for use as input to high resolution computer models.

To verify the credibility of the intervisibility data generated by the Waterways Experiment Station (WES) Terrain Factor Analysis.

The specific objective of the phase was to obtain line of sight, i.e., intervisibility, data between a number of simulated, defensively employed SHILLELAGH, TOW, and DRAGON missile systems and a simulated, advancing tank force in an assumed mid-intensity European conflict setting. Similar data were collected on the sites at Hunter Liggett Military Reservation (Phase IA) and two sites at Ft Lewis, Washington (Phase IL).

II. Conduct of the Experiment

Each Phase IE site utilized was a 2 km x 5 km rectangle, ordinarily with defensible terrain near one end of the site's long axis. Since most sites were in civilian areas, no alterations of the physical features of any of the sites were made, other than addition of equipment required for experimentation.

On the first day of experimentation on each site, a mechanized infantry officer was given the mission of selecting either 30 or 36 (depending on the amount of suitable terrain available) ATM positions; the large number of positions was necessary to attain the required data confidence level. A set of three tri-colored wooden panels (ATM panels) was erected on each position selected. Blue, red and yellow color bands on the ATM panel represented the height above ground of the SHILLELAGH, M113-mounted TOW and the DRAGON, respectively.

Simultaneously with the selection and marking of the ATM positions, 10 tank trails were marked from the opposite end of the site, running toward the defended area; again, the number of tank trails used was to attain the required data confidence level. On one site, these tank trails were laid using tracked vehicles; on the remaining 11 they were laid by qualified tank commanders operating on foot. The trails were developed using the "rapid approach" tactic of advance, i.e., moving in a deployed manner, over the fastest and most direct route, on the widest front possible. By actual measurement, a "viewing point" was then established every 25 meters along each trail.

Following site erection, data collectors made intervisibility measurements of each ATM panel marker from each of the viewing points along

each trail. Measurements were made from two viewing heights, corresponding to the viewing heights of a tank commander (turret) and tank driver (hull) of a threat tank. From each of these heights data recorders were required to indicate what portion of each ATM panel could be seen. If the entire panel was not visible, they were required to indicate that portion that was visible plus the reason the remainder of the panel was not visible. The collected data were subjected to quality control tests and, where necessary, remeasured. The intervisibility portion of Phase IA was executed the same as Phase IE with these exceptions: actual tanks were used to lay the tank paths and two tactics of advance were used. The type data produced were the same as Phase IE. The design for Phase IL was the same as that for Phase IE.

III. Summary of Results

Two specific measures computed for each ATM position-tank path combination were:

a. Number of intervisibility segments (IVS) as a function of range from the defensive line to the fartherest point on the intervisibility segment, and

b. Length of the IVS as a function of range.

For example, as a tank approached the defensive line, if it became intervisible with defensive position 17 when it was 2200 meters from the defensive line (not necessarily 2200 meters from position 17) and went out of sight of position 17 when it was 1400 meters from the defensive line, this would be counted as one IVS at a range of 2200 meters and was 800 meters long.

The mean number of IVS ($\overline{N}$) represents the number of opportunities an ATM system would have to detect an advancing armor element. Table 1 illustrates typical values of $\overline{N}$. The intervisibility data were evaluated for six range intervals, two tank heights (low was 4 feet and high was 7 feet), and three ATM system heights (blue was 116"; red 72"; and yellow 44"). Examination of the data from all sites indicates that:

The mean number of IVS is highly dependent on range, however, this dependency relationship was unique for each site.

Long range ATM weapons (>3000 meters) would have little opportunity to detect advancing armor in the NORTH GERMAN PLAIN area.

In the FULDA GAP area many detection opportunities exist for the longer ranges (>3000 meters).

N varies appreciably from site to site. The range of values was less among the FULDA and HOHENFELS sites ($\overline{N}$ = 3 to 4) than the NORTH GERMAN PLAIN sites ($\overline{N}$ = 1 to 6).

In a general sense, $\overline{N}$ is independent of the viewing condition. For example, on one site there was only a three percent difference in $\overline{N}$ between the two viewing condition extremes, "low-yellow" and "high-blue."

However, $\overline{N}$ is not sufficient to determine whether an advancing threat vehicle could be engaged by an ATM system. To make such a determination, it is necessary to know if the vehicle was intervisible with the ATM system for a sufficient length of time to permit engagement. This information is presented on the following pages.

Table 1 - MEAN NUMBER OF IVS PER AT/PATH (N) FOR ONE FULDA SITE

Condition		Range Interval (Meters)						
Tank Height	Upper ATM Height (Inches)	0 1000	1000 1500	1500 2000	2000 2500	2500 3000	>3000	Total
Low (4 ft)	Blue (116)	.4773	.2159	.6591	.5227	.7955	1.3352	4.0057
	Red (72)	.4886	.1932	.6591	.5000	.7670	1.3295	3.9375
	Yellow (44)	.4943	.1932	.6591	.4886	.7557	1.3295	3.9205
High (7 ft)	Blue (116)	.2841	.2216	.6136	.5909	.8239	1.3352	3.8693
	Red (72)	.2841	.2045	.6136	.5739	.8182	1.3295	3.8239
	Yellow (44)	.2955	.1932	.6080	.5568	.7955	1.3239	3.7727

The IVS length distribution along with an analysis of it is presented in the next section.

IV. Vulnerability as a Function of IVS

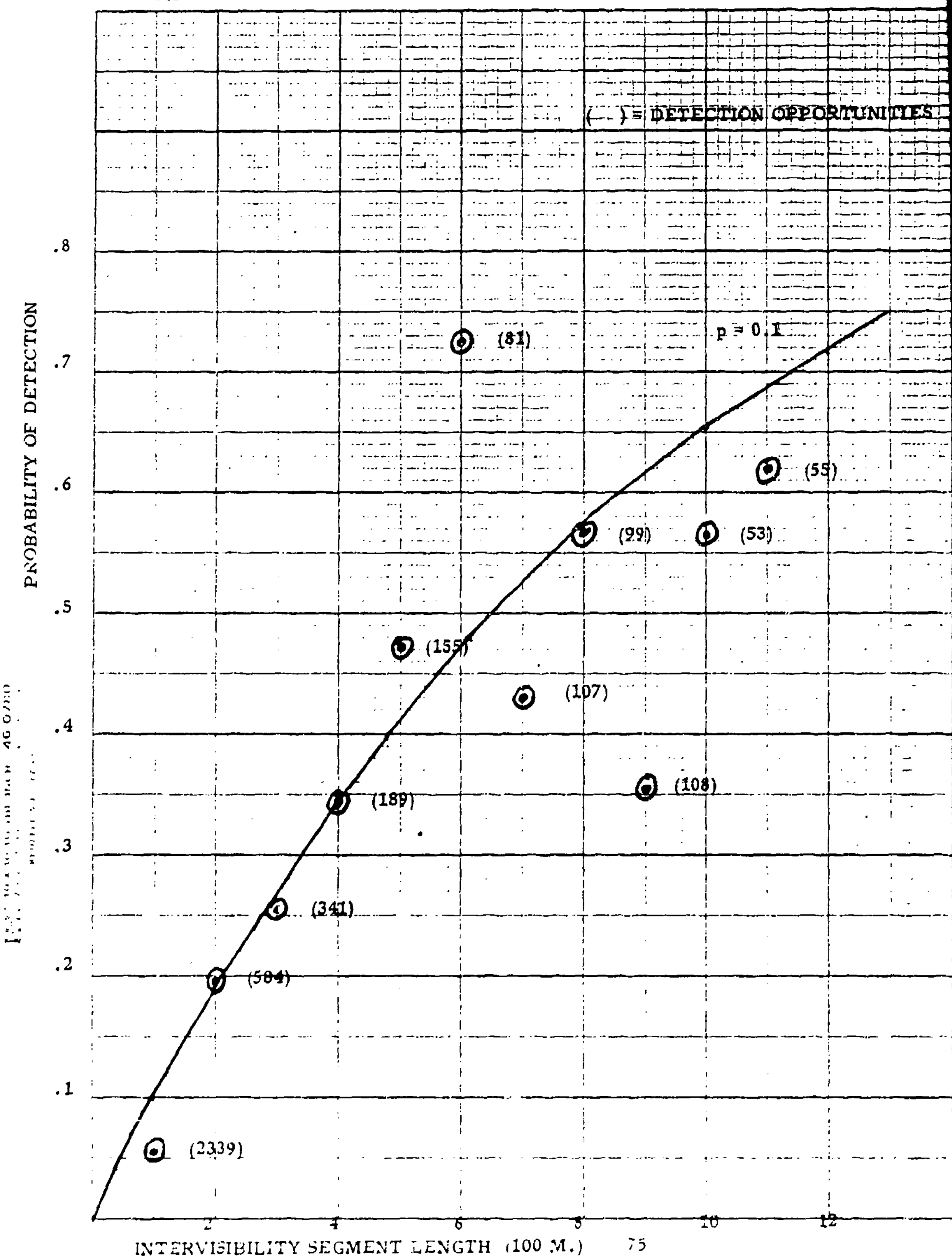
In Phase IB at Hunter Liggett in addition to the IVS data gathered on the two sites, detection rates were also examined. This experiment consisted of requiring 6 vehicles to simultaneously traverse 6 of the 10 preselected trails, while some of the 36 defensive positions were manned with players attempting to detect the advancing vehicles. Each time an advancing vehicle became intervisible (that is, was traversing a new intervisibility segment) the player manning the defensive position was to attempt to detect and if successful to immediately transmit his detection to the central computer through a controller.

On Site A there were a total of 4326 opportunities for a defensive player to detect an advancing vehicle. In 854 of these detection opportunities did detection actually occur producing an overall probability of detection (given an opportunity) of .197. The probability of detection is essentially independent of range from the observer to the vehicle. For five range bands between 0 and 3000 meters the overall probability of detection, disregarding segment length, was between .2 and .25. For those opportunities where the range was greater than 3000 meters the probability of detection was .13.

On Site B there were 4193 detection opportunities, 1211 resulting in detections, yielding a probability of detection, given an opportunity, of .289. On Site B the probability of detection did appear to be range dependent, varying from a probability of .33 at ranges less than 1000 meters to a probability of .08 at ranges between 2500 and 3000 meters.

The data analysis which follows combines all range bands. Although, as pointed out above, this is not entirely appropriate on Site B, careful examination of the raw data reveals that it is reasonably accurate because of small sample sizes at the longer ranges. Charts 1 and 2 present the observed percentage of detections as a function of the length of the intervisibility segment which represented the opportunity to detect. (Circled points) On both sites the empirical values are quite well behaved up to segment lengths of 600 meters. For segment lengths greater than 600 meters because of decreasing sample size, as well as lack of independence of observations, the empirical values are more erratic.

CHART 1: DETECTION RATES   SITE A



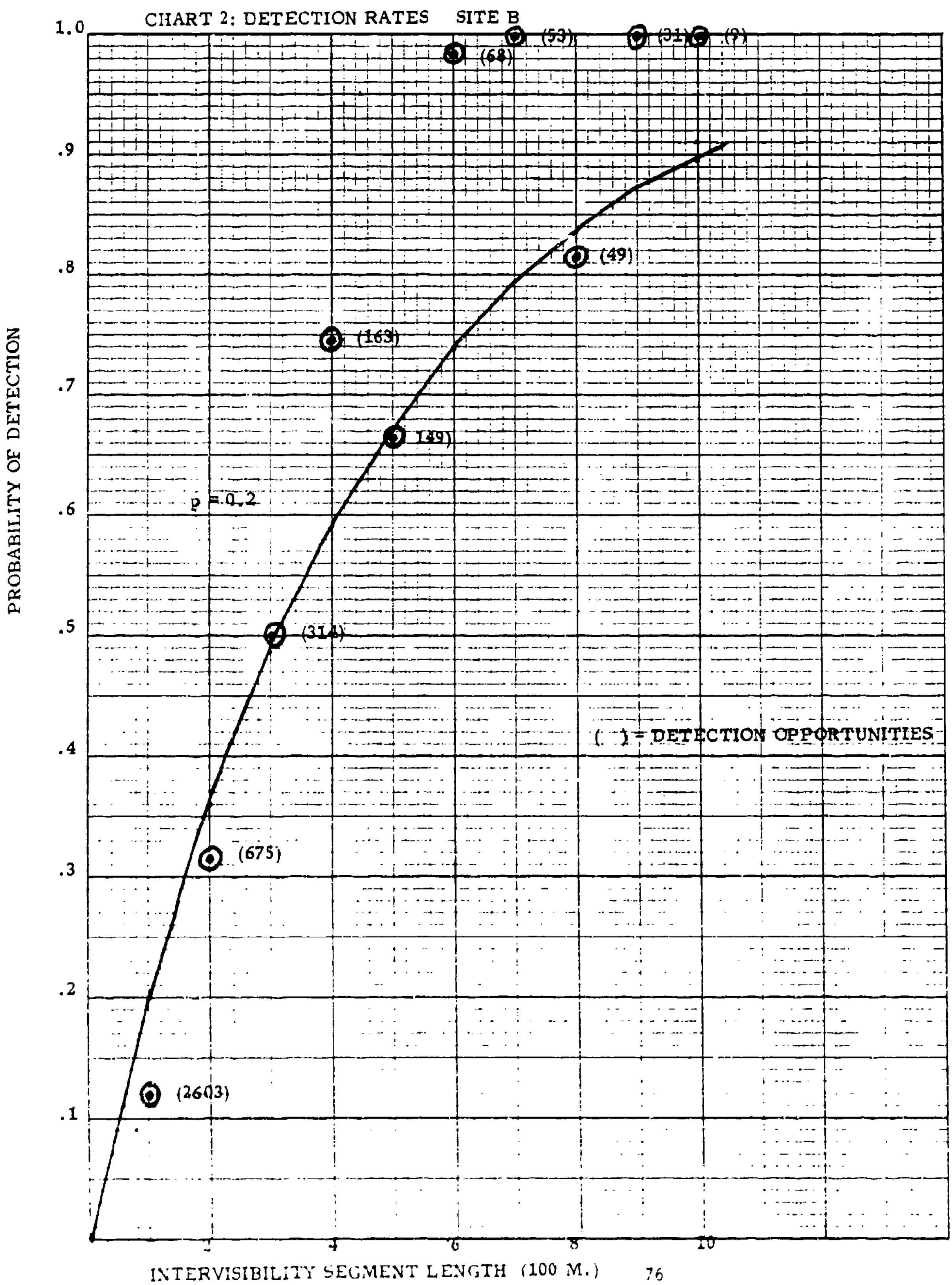


CHART 2: DETECTION RATES SITE B
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
PROBABILITY OF DETECTION
(68)
(53)
(31)
(9)
(49)
(163)
149)
p = 0.2
(314)
( ) = DETECTION OPPORTUNITIES
(675)
(2603)
2
4
6
8
10
INTERVISIBILITY SEGMENT LENGTH (100 M.)

Let us define a "section" as a 100 meter portion of a trail which is entirely intervisible from a given defensive position. If one assumes that the probability of detection for any given section is a constant, say P, then the theoretical detection curve is in the form of an exponential. A P = 0.1 produces the theoretical curve shown on Chart 1. For Site B the curve shown is for P = 0.2. Surprisingly on each of these charts for the short intervisibility segment lengths the curves over estimate the probability of detection and for longer segment lengths the curve tends to under estimate the probability of detection.

In order to further study this phenomenon the empirical data were examined to determine the length of the intervisibility segment remaining following an actual detection. Charts 3 and 4 show the distribution of segment lengths remaining after detection. Also shown are the distributions of total intervisibility segment lengths. Paradoxically, the expected length of a segment remaining after detection is considerably greater than the expected length of an entire intervisibility segment! A plausible explanation for this apparent contradiction is that for short intervisibility segments the probability of detection is quite low since the vehicle is more likely to be in clutter during the entire segment. For the longer intervisibility segments, the vehicle is more likely to come clearly into the open.

Charts 5 and 6 show the probability that the vehicle will remain continuously exposed after a detection for a given time if he proceeds down the predesignated trail. Since this is a function of the speed of the vehicle, three selected speeds are presented on the chart.

A glance at these charts convinces one that there is a reasonably high probability that if he detects a tank, it will remain visible long enough for him to get a shot at it. If, for example, it takes a gunner 15 seconds to fire after detection and it takes the missile 15 seconds to fly to the target, his probability of being there in time varies from a low of .35 on Site B with a 20 MPH target to a high of .71 on Site A with a 5 MPH target.

V. Summary

The primary purpose of this paper is to discuss the existence of a large volume of ground-to-ground intervisibility data. Also discussed are the method of collection of the data and a sample of the kinds of analyses which are ongoing. Comparisons of these data with other

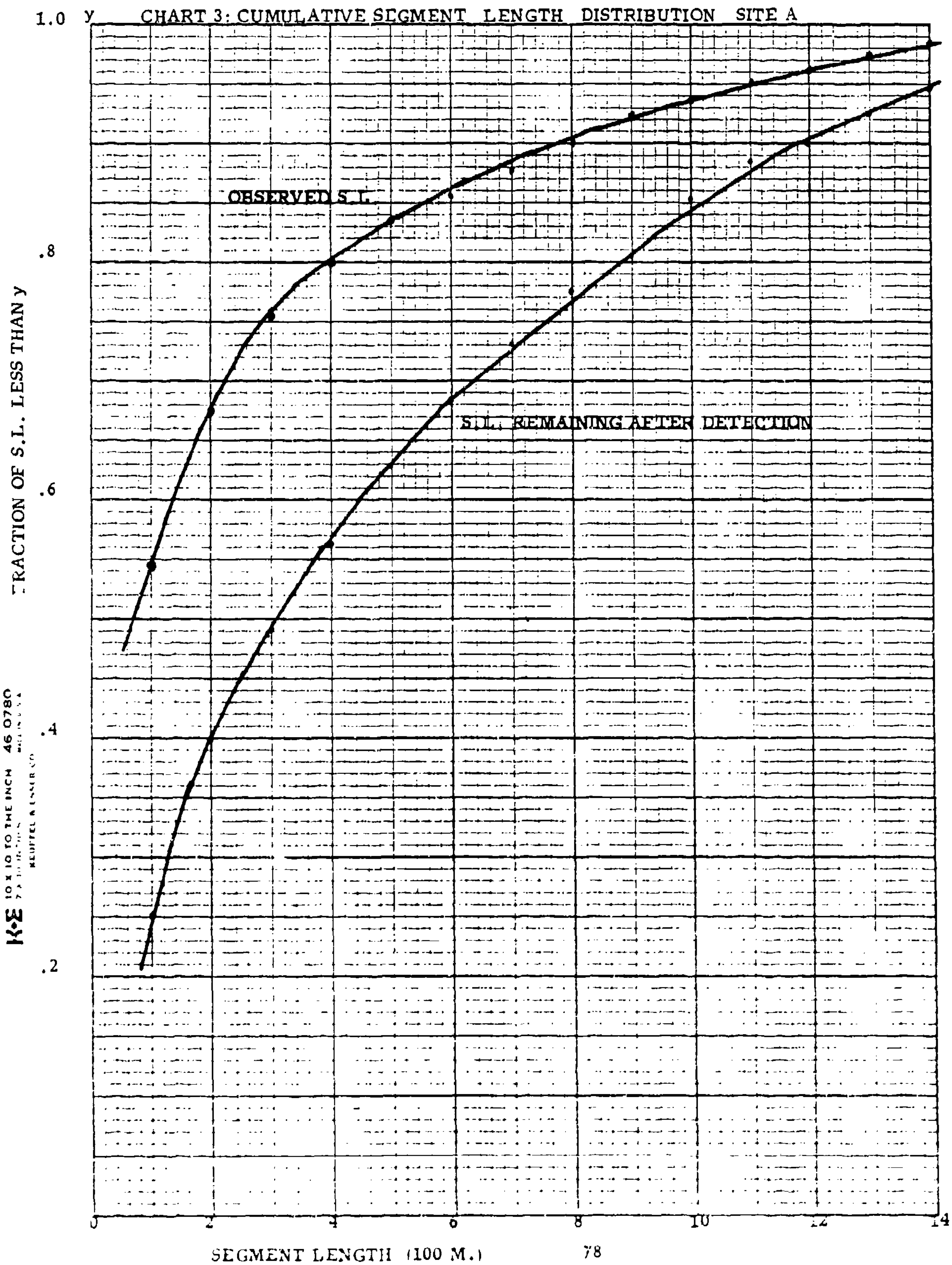


CHART 3: CUMULATIVE SEGMENT LENGTH DISTRIBUTION SITE A
1.0 y
.8
.6
.4
.2
FRACTION OF S.L. LESS THAN y
OBSERVED S.L.
S.L. REMAINING AFTER DETECTION
0
2
4
6
8
10
12
14
SEGMENT LENGTH (100 M.)
K-E 10 X 10 TO THE INCH 46 0780
KEUFFEL & ESSER CO.

CHART 4: CUMULATIVE SEGMENT LENGTH DISTRIBUTION SITE B

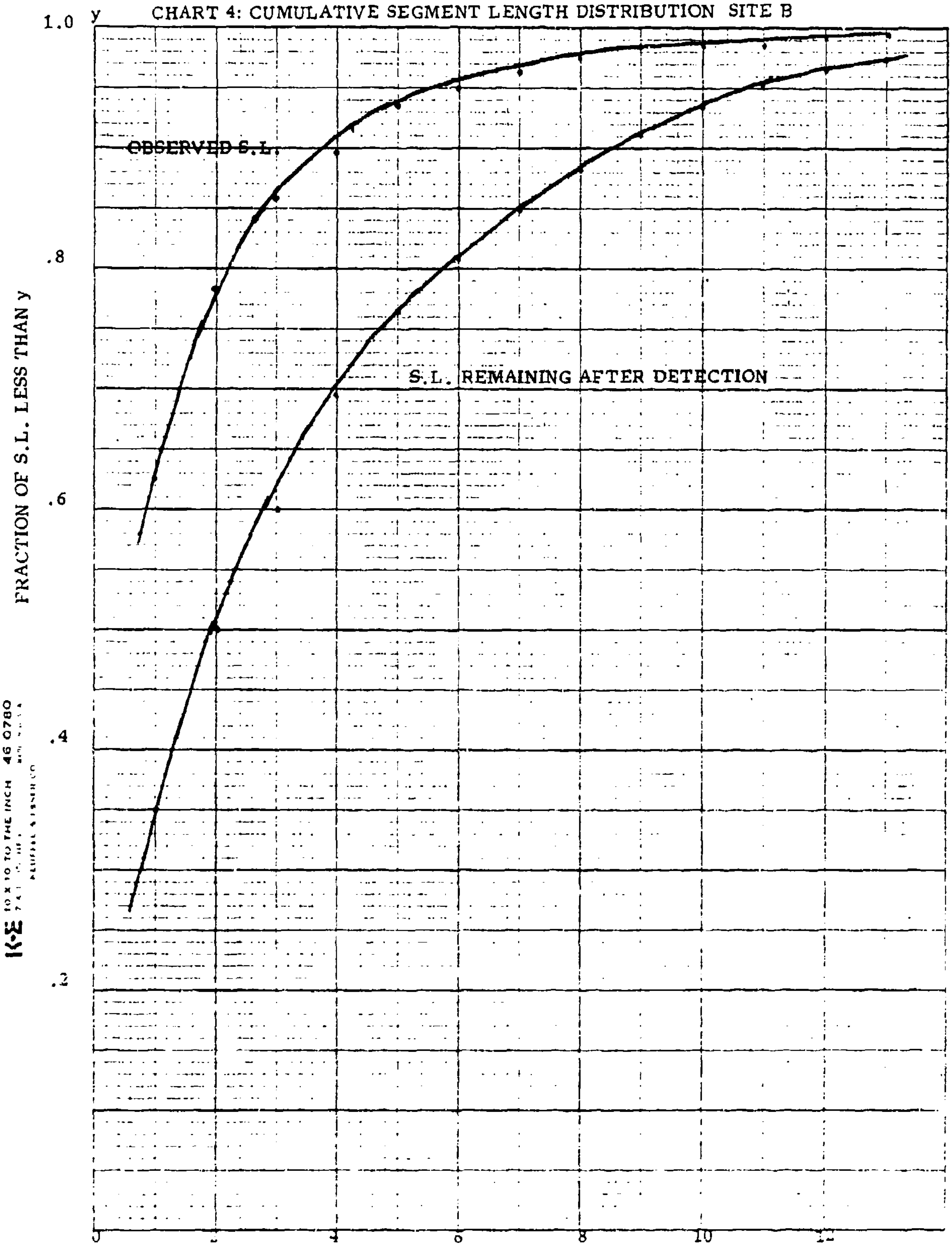


CHART 5: EXPOSURE TIMES SITE A

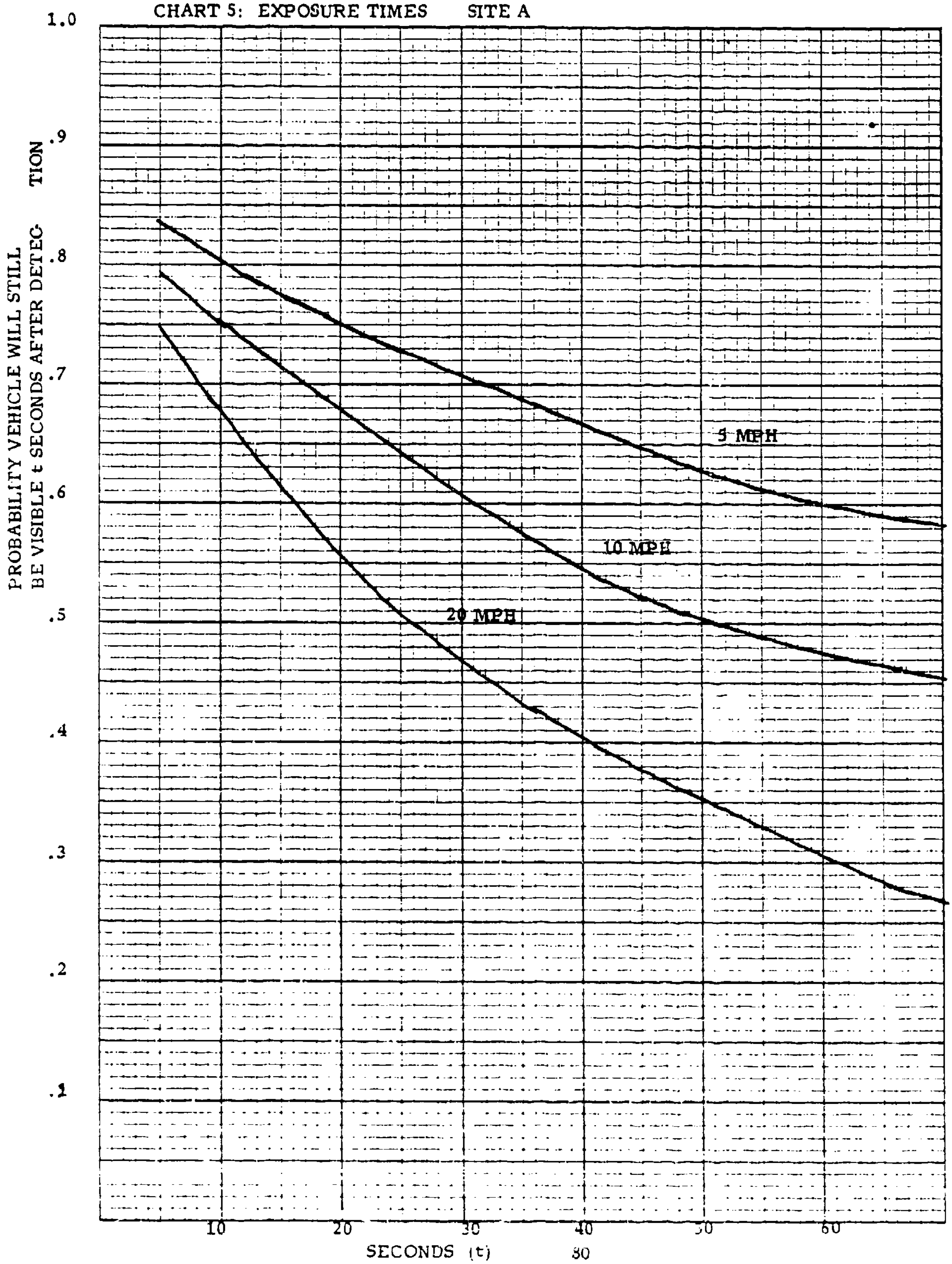
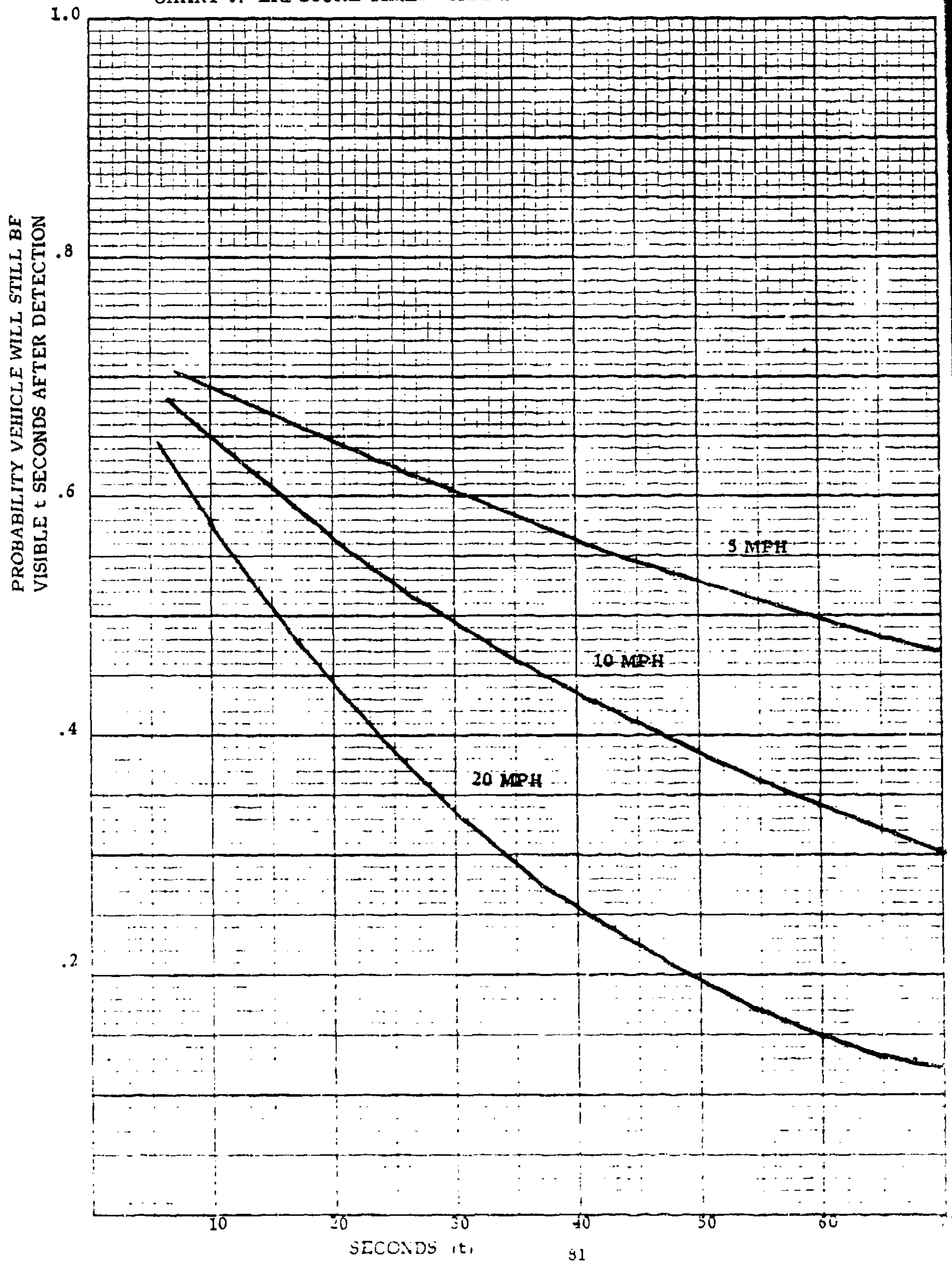


CHART 5: EXPOSURE TIMES SITE B



sets similarly gathered are in process. Personnel at the Waterways Experiment Station are also analyzing the data.

Two major results which have emerged are:

a. It is very difficult to classify terrain as a function of intervisibility characteristics and

b. On a tactically realistic rapid attack route, a tank is highly vulnerable to a defensively deployed ATM force.

AD P000 603

HELICOPTER MASKING ANALYSIS

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The successful employment of a helicopter-borne TOW missile system is partially dependent on the availability of masks to conceal the approach to, and withdrawal from, firing positions. In this regard the Engineer Strategic Studies Group (ESSG) has evaluated terrain in the USAREUR/Seventh Army area to determine the availability of masks for attack helicopters using "pop-up" tactics.

The ESSG effort was accomplished in two separate actions. The first was a study titled Incidence of Terrain Masking Opportunities in the USAREUR/Seventh Army Area, and has since been published as Appendix I to the Combat Developments Command, Advanced Attack Helicopter Task Force Report, dated June 1972, ACN 20268. This particular study estimated the percentage of target points along three probable enemy approach routes that could be observed from topographic masks. The approach routes examined extended from the East German border to the Rhine River.

The second ESSG action was a study titled Helicopter Masking Analysis which was accomplished at the request of the Deputy Under Secretary of the Army (Operations Research). This study evaluated the availability of masks by application of two different procedures, one of which was simply an extension of the previous ESSG effort. The other procedure was directed at estimating the percentage of total area which could be observed from topographic masks. Unlike ESSG's first effort, the second involved a study of the area contained in initial battalion defensive positions. This action, as well as the first, considered the effect of vegetation on topographic masks.

Since the procedure used in the first ESSG action was essentially duplicated in the second, this paper will discuss in detail only the two procedures used in the second action. The following discussion is devoted to an explanation of the two procedures used and results obtained, a comparison of the two procedures and, finally, the effect of using forests and built-up areas as masks. For convenience the two procedures have been identified as a point-by-point analysis and a continuous frontal analysis.

Point-by-point procedure. The point-by-point procedure generally consisted of determining the fraction of sample target points that could be observed from a helicopter using a topographic feature for a mask. The analysis was conducted on 1:25,000 scale map.

The relative location of each sample target point, helicopter, and mask is shown at Figure 1. Throughout the analysis the helicopter was fixed at 3,100 meters from the target point. This represents the maximum effective range of a TOW missile and a point where the TOW expectation of kill is much greater than the air defense weapons of its probable targets. The distance "R," the main element of the data collection effort, represents the range of the most distant mask from the target within the range limitation, 3,100 meters, of the TOW. Distance "R" is a measure of mask

HELICOPTER "POP-UP" BEHIND TOPOGRAPHIC MASK

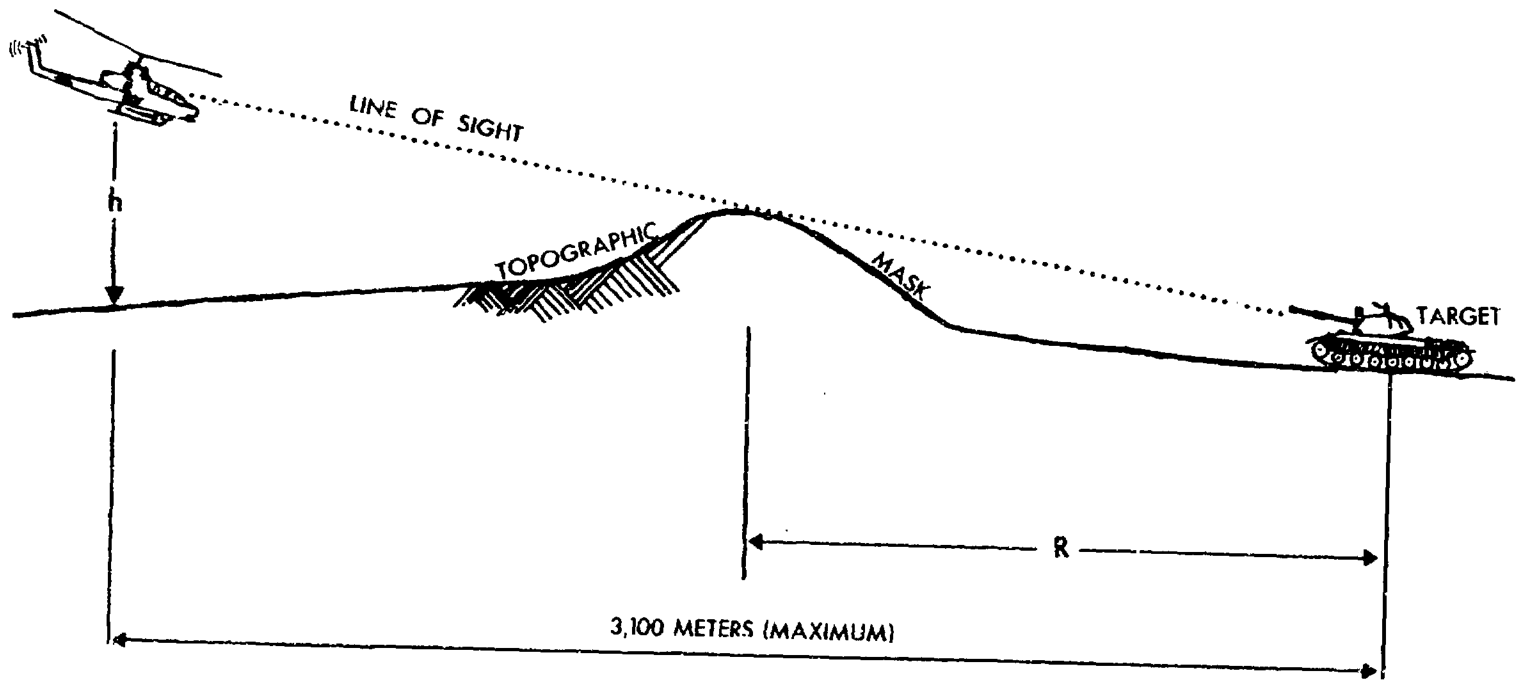


Figure 1

quality since the relative distance between mask and target fixes helicopter "H" at 3,100 meters. As "R" decreases, "H" increases as well as the helicopter vulnerability to weapons other than the target weapon. "H" is not only a function of the slant angle but also the missile firing error which increases with distance from the helicopter. Thus, due to the firing error, the probability of the missile hitting the mask increases with distance between helicopter and mask or, similarly, with decreasing "R."

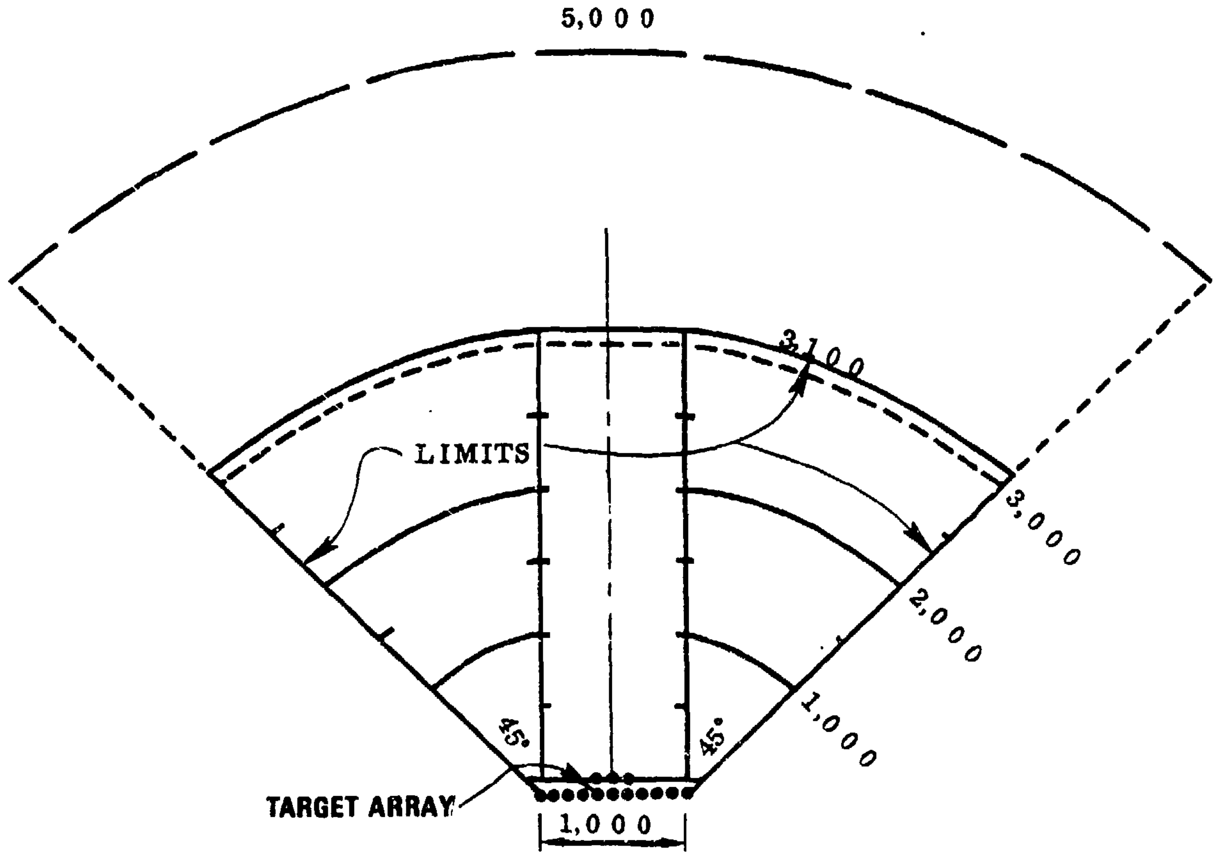
Topographic features and vegetation were allowed to restrict the number of available masks. The former had to provide at least 15 meters projected vertical cover at 3,100 meters to insure that the helicopter could fly "nap-of-the-earth" into firing position. In the latter case, if vegetation existed in the vicinity of the target, topographic features were discounted as providing a mask because of the disruption to line-of-sight.

Sample target points were located by first establishing 30 type battalion positions on the maps. Each position was 3 km wide by 10 km deep. The 30 delimit 11, 8, and 11 battalion positions, respectively across the Bad Hersfeld, Fulda, and Meiningen approaches. Four battalion positions were selected at random from each of the three groups. Three parallel, equidistant penetration lines were passed through each battalion position. Six target points were marked at 2-km intervals along each line of penetration, with the first target point established at a 3,100-meter range forward of the FEBA. The sixth target point on each line could be fired upon from masks within the depth limitation established for the type battalion position. This sampling procedure provided a total of 216 target points.

The type target postulated for the analysis and positioned at each target point was a Soviet armored company. It consisted of three tanks followed by a total of 10 tanks and APCs, and one air defense unit. A 100-meter interval was assumed between all vehicles which resulted in a company front of 1,000 meters. Extraction of the data from the topographic maps was facilitated by the template shown at Figure 2. Any vehicle within the target array was assumed capable of firing at a visible helicopter. Consequently, the center of the target array on the template was positioned over each sample target point with the template centerline coincident to the line of target penetration. The frontal rectangle (1,000 x 3,000 meters), left octant and right octant on the template were searched independently to find the range to the most distant control mask within 3,100 meters. All intermediate masks were ignored. A profile was drawn for each control mask to establish its validity and the required helicopter height at the 3,100-meter range. The 3,100-5,000 meter interval on the template was checked to ensure concealed helicopter access to its firing position. Finally, the area in the vicinity of the target point was checked for vegetation that would obstruct visual observation of the target and, thus, discount a topographic feature as a mask.

Figures 3 and 4 show the distribution of ranges to the most distant mask resulting from application of the procedure described above. In each figure the horizontal axis expresses the distance between the target

OUTLINE LIMITS (TEMPLATE) OF POSSIBLE HELICOPTER FIRING POSITIONS



NOTES:

1. **All distances are in meters.**
2. **Template is reduced from 1:25,000 scale.**

Figure 2

DISTRIBUTION OF RANGES TO HELICOPTER MASKS
AT MAXIMUM RANGE FOR POTENTIAL TARGETS ALONG
APPROACH ROUTES AND WITHIN DEFENSIVE POSITIONS

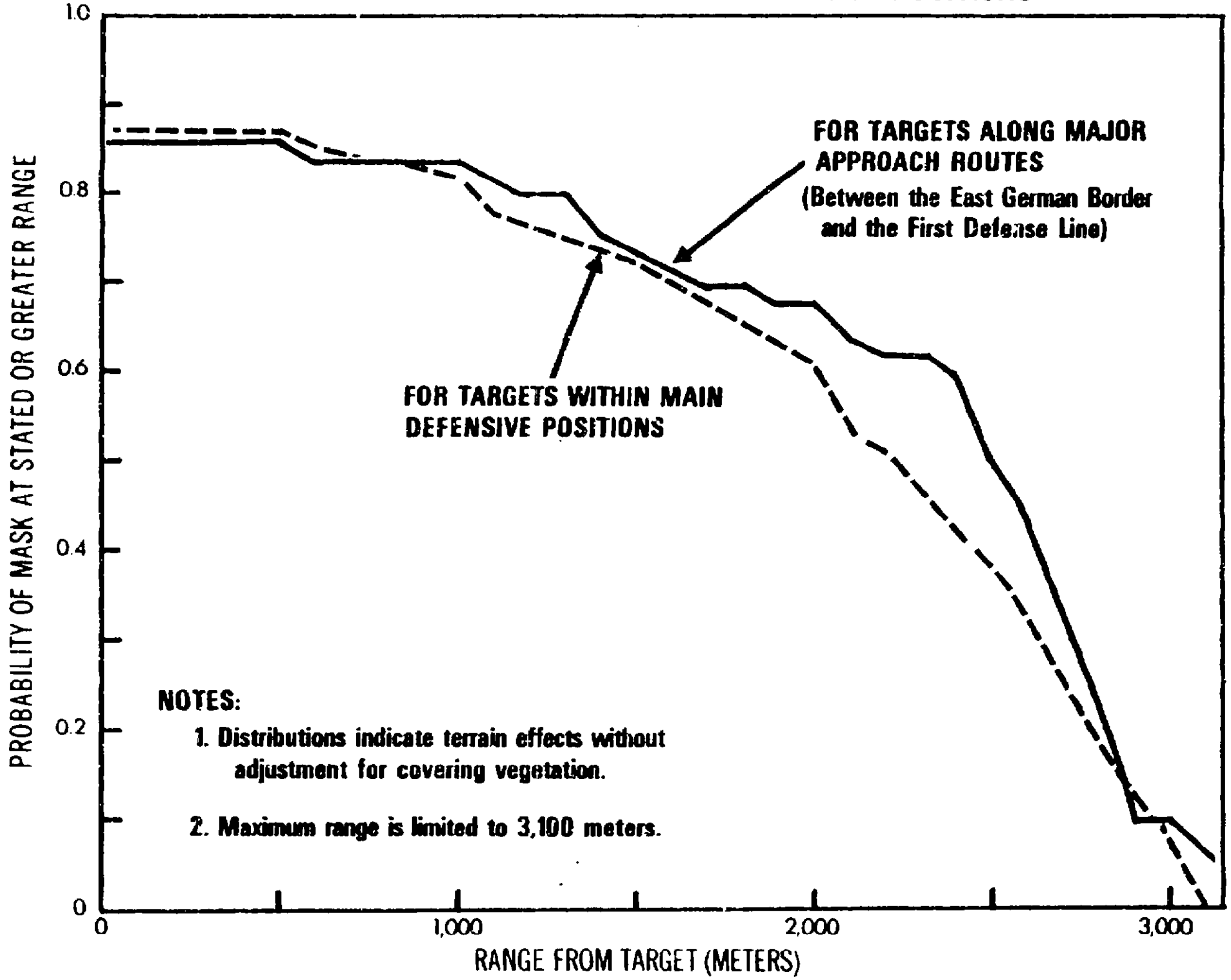


Figure 3

DISTRIBUTION OF RANGES TO HELICOPTER MASKS AT MAXIMUM RANGE FOR POTENTIAL TARGETS WITHIN DEFENSIVE POSITIONS

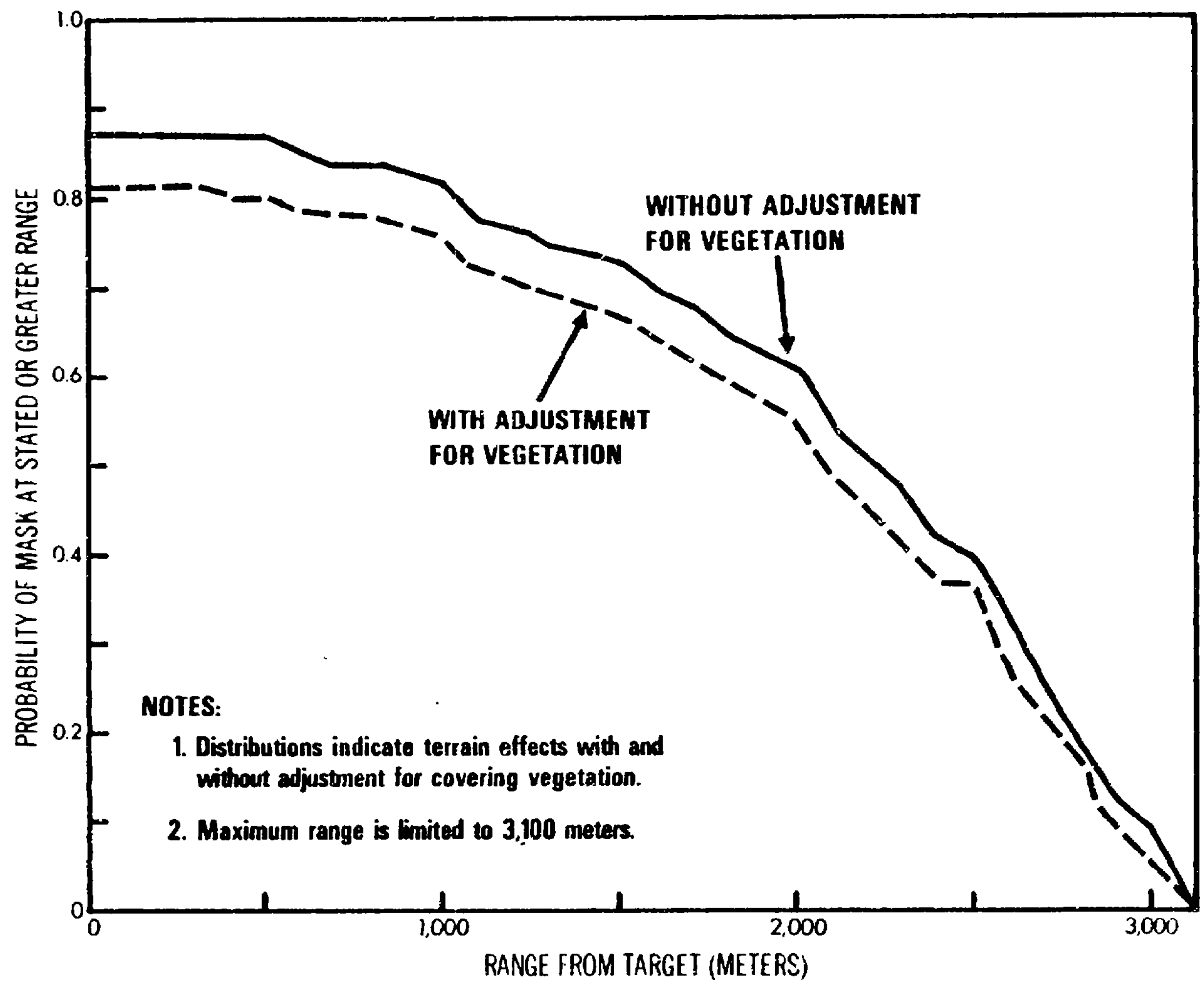


Figure 4

and the most distant mask. The vertical axis shows the fraction of target points with masks at plotted or greater ranges (but no more than 3,100 meters). The intercept of each distribution is the total probability of finding a usable mask in the area from which the sample target points were taken. The distributions shown represent a single mask for each target point whether it was found in the frontal rectangle or either of the octants.

Figure 3 shows two distributions. The dashed distribution represents the results of the initial ESSG action. It should be recalled that the first action analyzed mask availability along approach routes while the second action dealt with battalion defensive positions. Both distributions reflect only terrain effects and do not include adjustment for covering vegetation.

The plotted distribution for targets within battalion defensive positions lies mostly below the approach route distribution. With allowance for sample sizes, sampling variation, and the possibilities of error, any differences between the distributions of 0.05 or less should be regarded as insignificant; differences between 0.05 and 0.10 as marginal; and differences of 0.10 or more as significant. The terrain within the battalion positions and along approach routes is equally likely to provide at least one helicopter mask within 3,100 meters of the target; the difference between the distributions at zero range is insignificant. Differences between the distributions at greater ranges vary. For example, the difference at 2,400 meters is about 0.17 and is significant. Without allowance for vegetation, it can be concluded that suitable masks are about as likely to occur within defensive positions as along major approach routes where they are distributed somewhat more favorably toward higher ranges and, therefore, are of superior quality.

The two distributions in Figure 4 reflect terrain effects with and without adjustment for covering vegetation. Both correspond to target points within battalion defensive positions. Adjustments for vegetation provide a reduction for target obscuration but do not allow for additional helicopter firing positions. The distribution with adjustment for vegetation is as much as 0.07 lower than the unadjusted distribution. Although point-by-point vegetation-adjusted data are not available for the approach route targets portrayed in Figure 3, vegetation there should yield a similar reduction. Other adjusted data (not shown) that include but do not isolate the approach route targets of Figure 3, produce reductions similar to those for defensive positions. It is probably safe to conclude that adjustment for vegetation reduces both Figure 3 distributions but preserves the relation between targets within defensive positions and targets along major approach routes.

Distributions of helicopter altitudes required to observe targets from 3 km are shown in Figure 5. These data represent frontal masks only. The upper curve was generated from data collected along the major approach routes, and the lower curve represents the distribution of altitudes within battalion defensive positions. For both distributions, approximately 94 percent of all altitudes fall below 200 meters. The results also indicate that somewhat lower altitudes were required along the approach routes; 88 percent of all altitudes fell below 200 meters

DISTRIBUTION OF HELICOPTER ALTITUDES REQUIRED TO VIEW TARGETS FROM THREE KILOMETERS

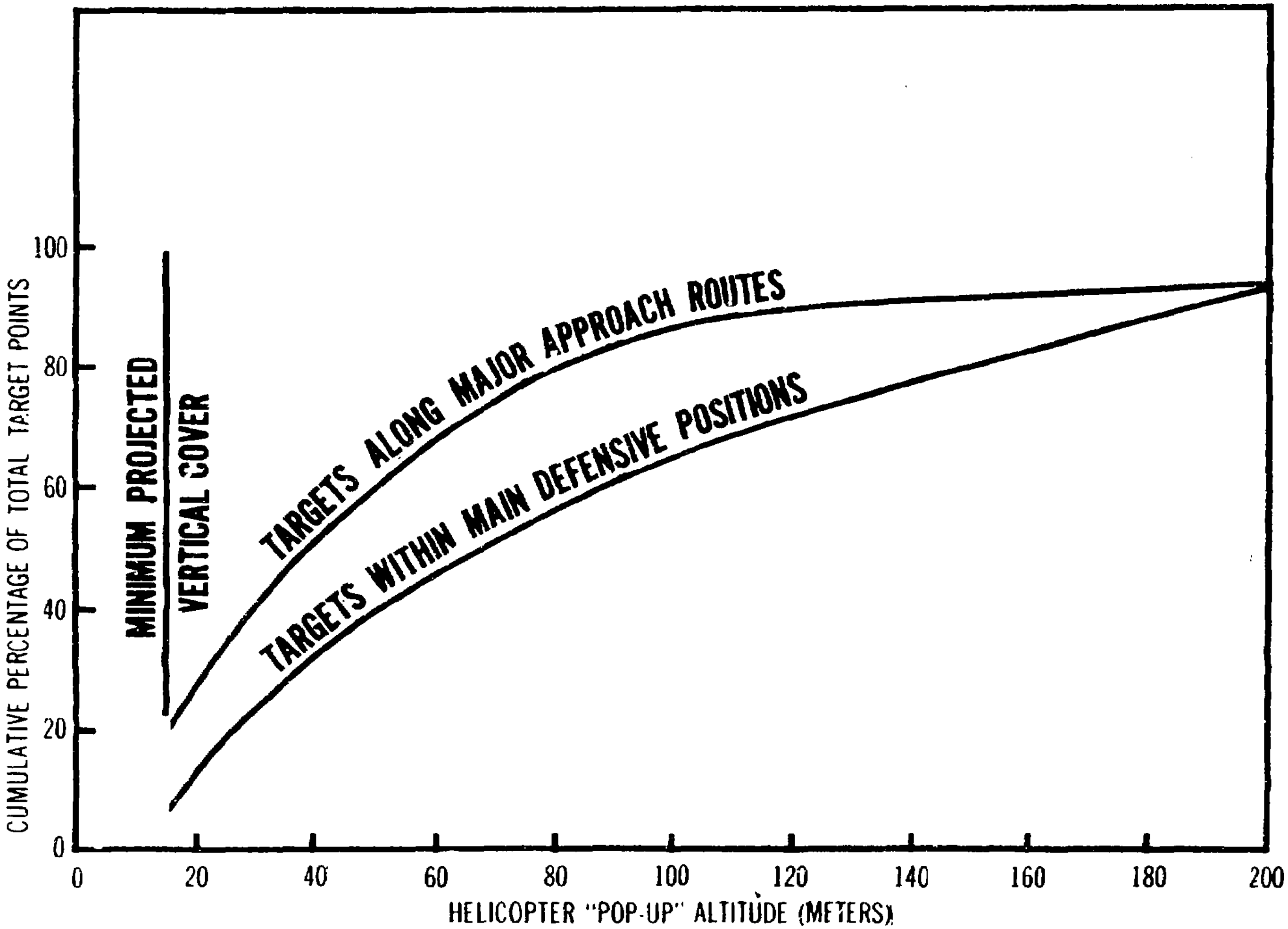


Figure 5

for those target points within the defensive positions. Sixty percent of all altitudes fell below 50 meters for the approach route targets, compared to 40 percent within the defensive positions.

Continuous frontal analysis. The continuous frontal analysis assessed the fraction of the total battalion area observable from helicopters using "pop-up" tactics. The results were adjusted for vegetation to the extent that observable area was reduced for target obscuration. The battalion positions used were the same as in the point-by-point analysis, but instead of analyzing four positions for each of the three approach routes, only three positions were randomly selected.

Each position was analyzed by developing profiles along straight lines through the position from front to rear. Thirteen such profiles were established evenly across the position width; they extended from a 3,100-meter range forward of the FEBA to the position rear boundary. The analysis considered frontal sampling of masks on a continuous basis along each profile, but did not include the identification of side masks. Adjacent observable profile segments and the map area between profiles were considered when computing the observable area for the position.

To obtain the distribution of observable area within each position, successive 600-meter bands across the position width were established. Results from the masking analysis along each profile were segmented so that the observable fraction of the total band area could be identified separately. The analysis was limited to 17 600-meter bands, which allowed firing from within the established rear boundary for the battalion position.

To be considered a suitable firing position, a mask was required to provide at least 15 meters projected vertical cover for the helicopter at a range between 2,500 and 3,100 meters from potential target points along the profile. A maximum helicopter altitude of 200 meters above ground was also required to preclude unrealistic "pop-up" altitudes resulting from steep reverse slopes. Members of the Advanced Attack Helicopter Task Force were asked their opinions regarding this limitation; it was agreed that a 200-meter altitude would be reasonable for this purpose.

In analyzing the position, the effects of forests on the observable areas were considered. When forests overlaid the target point or profile segment under analysis, this reach was not included as observable area. Also, when intermediate forests obscured the target point or profile segment on the target side of the forest limits, the area subjected to this shadow effect was not considered observable area disregarding the forest effects (i.e., based on topographic masking only).

Distributions of observable areas were developed for each battalion defensive line approach; this was done by averaging the results generated for the three battalion positions analyzed in detail. Bad Hersfeld, Fulda, and Meiningen positions are reported in Figures 6, 7, and 8 respectively. The vertical axis of each figure indicates the observable area as percent of the total band area, and the horizontal axis indicates the successive bands through the positions. The distributions considering

DISTRIBUTION OF OBSERVABLE AREAS
BAD HERSFELD APPROACH

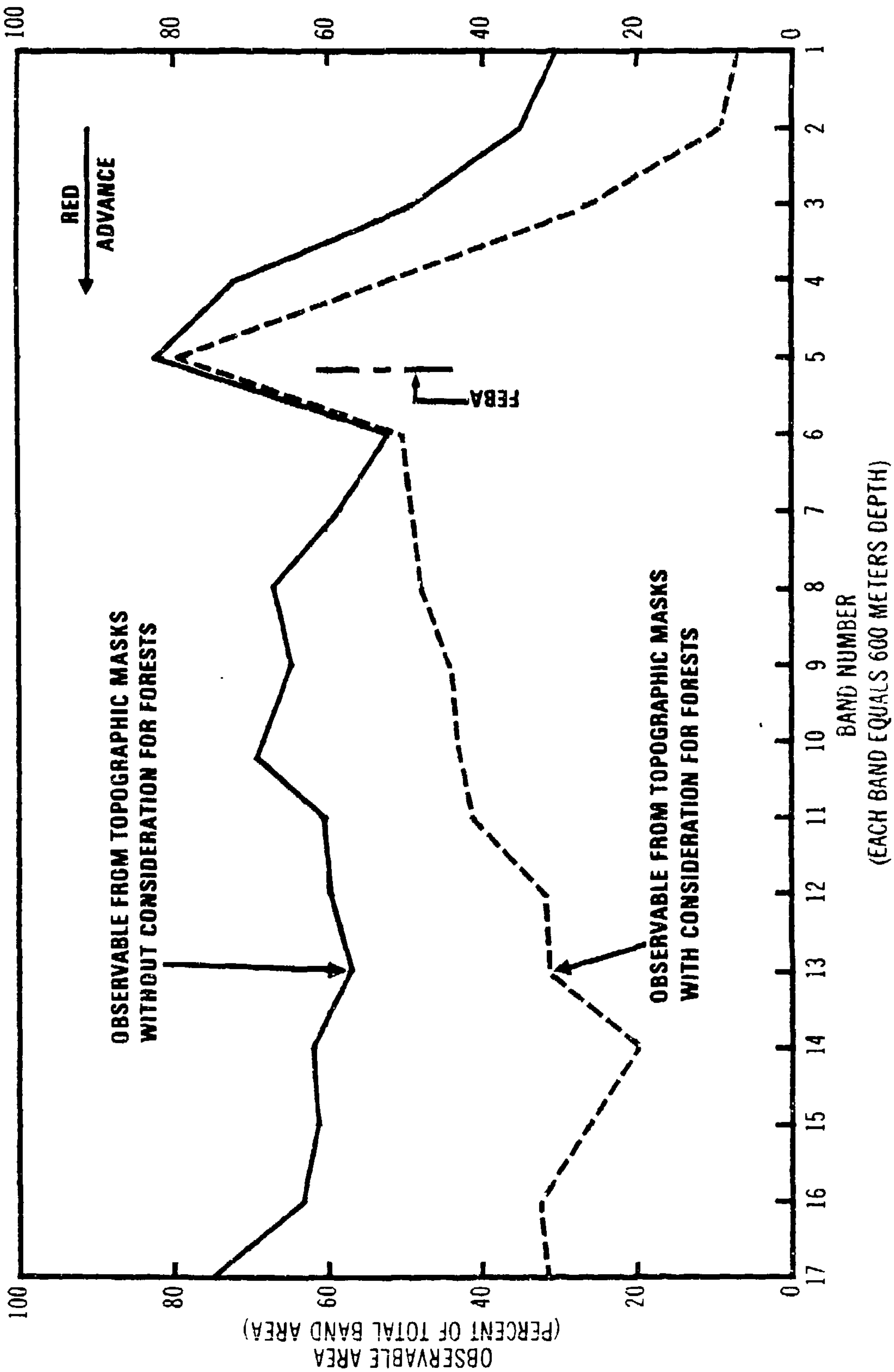


Figure 6

DISTRIBUTION OF OBSERVABLE AREAS
FULDA APPROACH

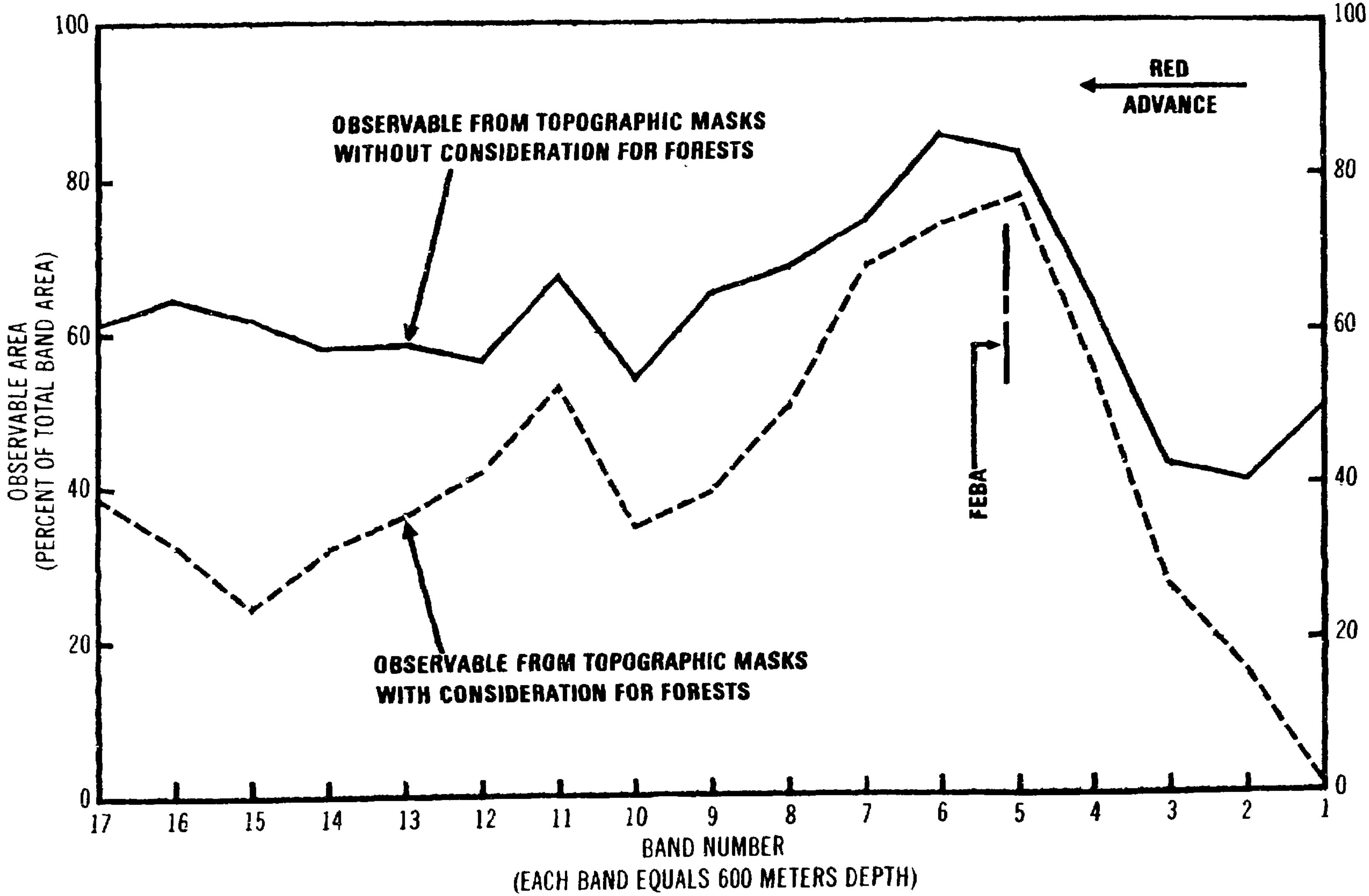


Figure 7

DISTRIBUTION OF OBSERVABLE AREAS
MEININGEN APPROACH

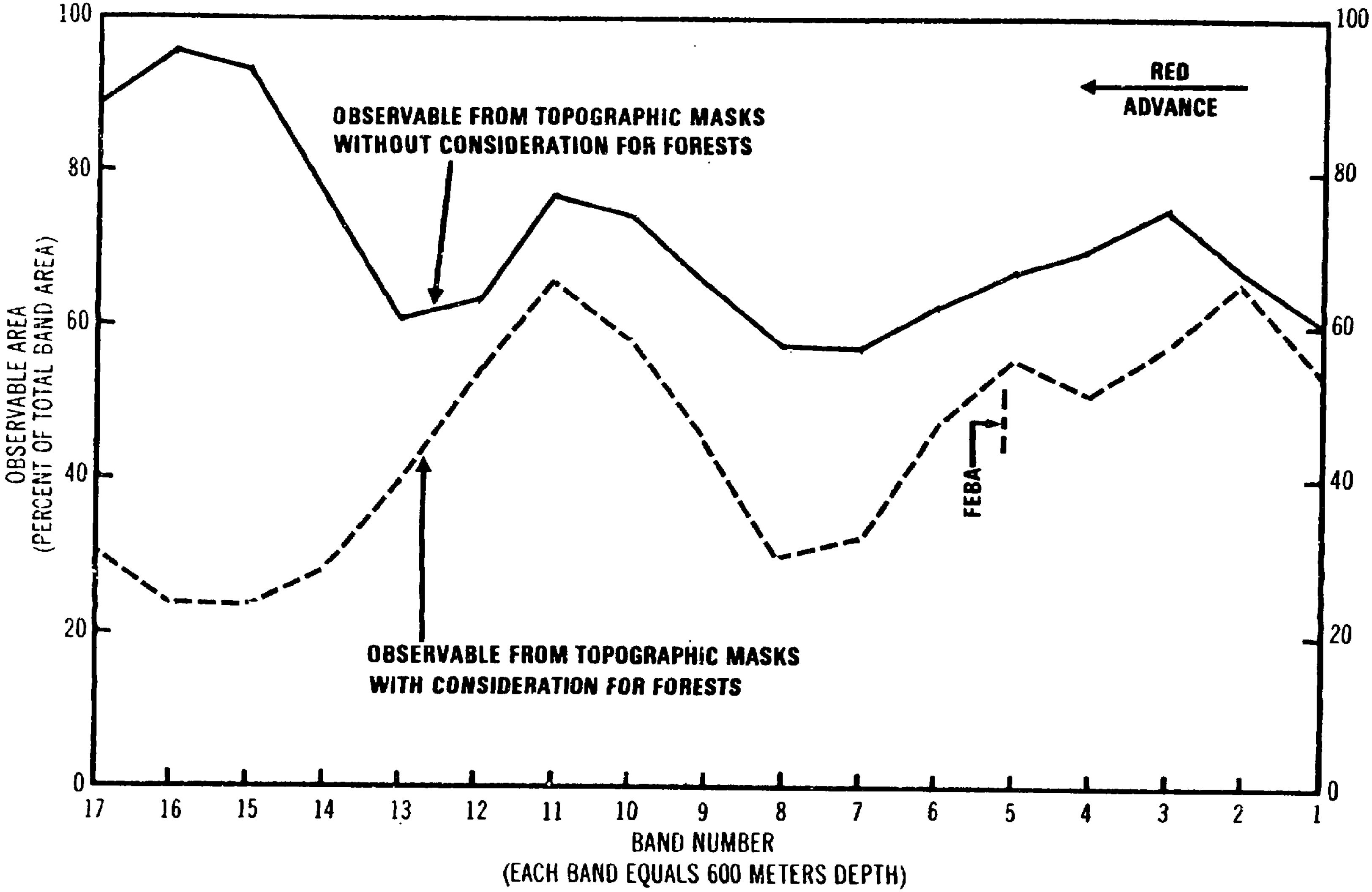


Figure 8

the effects of forests (the lower line in each figure) are by far the more important of the two distributions shown, since they represent a truer assessment of the approaches from the standpoint of air-to-ground observability. Distributions disregarding the effects of forests are presented for comparison purposes to indicate the incremental values between the two sets of data. Figure 9 shows the average conditions for the first defensive line; the results from the nine battalion positions were averaged to develop the distributions shown. These distributions show that the positions in the vicinity of the FEBA contain a relatively higher percent of observable area. The percent of observable area generally decreases toward the rear of the defensive line.

Average observable areas for individual positions, approaches, and the first defensive line are shown in Figure 10. Observable areas are indicated as a percent of the total area for all 17 bands. One set of results was based on topographic masks only (without considering forest effects), and another considered the effects of forests.

Comparison of results. A check of the point-by point analysis sought to correlate the 18-point sampling results with those generated using the continuous frontal analysis. Figure 11 depicts the results of this comparison. Results from the two independent analyses are compared for each of nine battalion defensive positions. The fraction of target points or area observable from masks were developed; one set of points considered topographic masks only (without forest effects) and another included forest effects. Results shown for the point-by-point analysis were generated using only frontal masks and limiting the sample to points which required helicopter altitudes of 200 meters or less. Changing these criteria caused the two methods of analysis (point-by-point and continuous) to admit masks on the same basis and, therefore, made their results comparable. Most of the paired estimates shown are remarkably close. The poorest correspondence occurred for Bad Hersfeld position number 8, where the differences are 0.318 and 0.202 respectively for estimates without and with consideration for forest effects. Bad Hersfeld position number 8 was reexamined using a more closely spaced point-by-point analysis (intervals of 200 meters instead of 2 km), 153 rather than 18 points were analyzed. Of the 153 target points, 100 possessed masks for the analysis without consideration for forest effects; the result (0.654) is consistent with that (0.626) estimated using the continuous analysis. The results considering forest effects were also consistent; the point-by-point analysis estimated 0.386 compared to 0.354 for the continuous analysis.

Effects of Forests and Built-up Areas as Masks. Up to this point only topographic masks have been discussed. Vegetation has been considered only to the extent that it obscured targets. Vegetation, however, as well as built-up areas, can also be used as masks. In this regard the masking potential of forests and built-up areas in the USAREUR/Seventh Army area was quantified in the second study conducted by ESSG.

Four categories of masks were identified and addressed. In descending order as to quality, they were the rear edge of forests, interior forest clearings, the front edge of forests, and built-up areas.

DISTRIBUTION OF OBSERVABLE AREAS
AVERAGE OF BAD HERSFELD, FULDA, AND MEININGEN APPROACHES

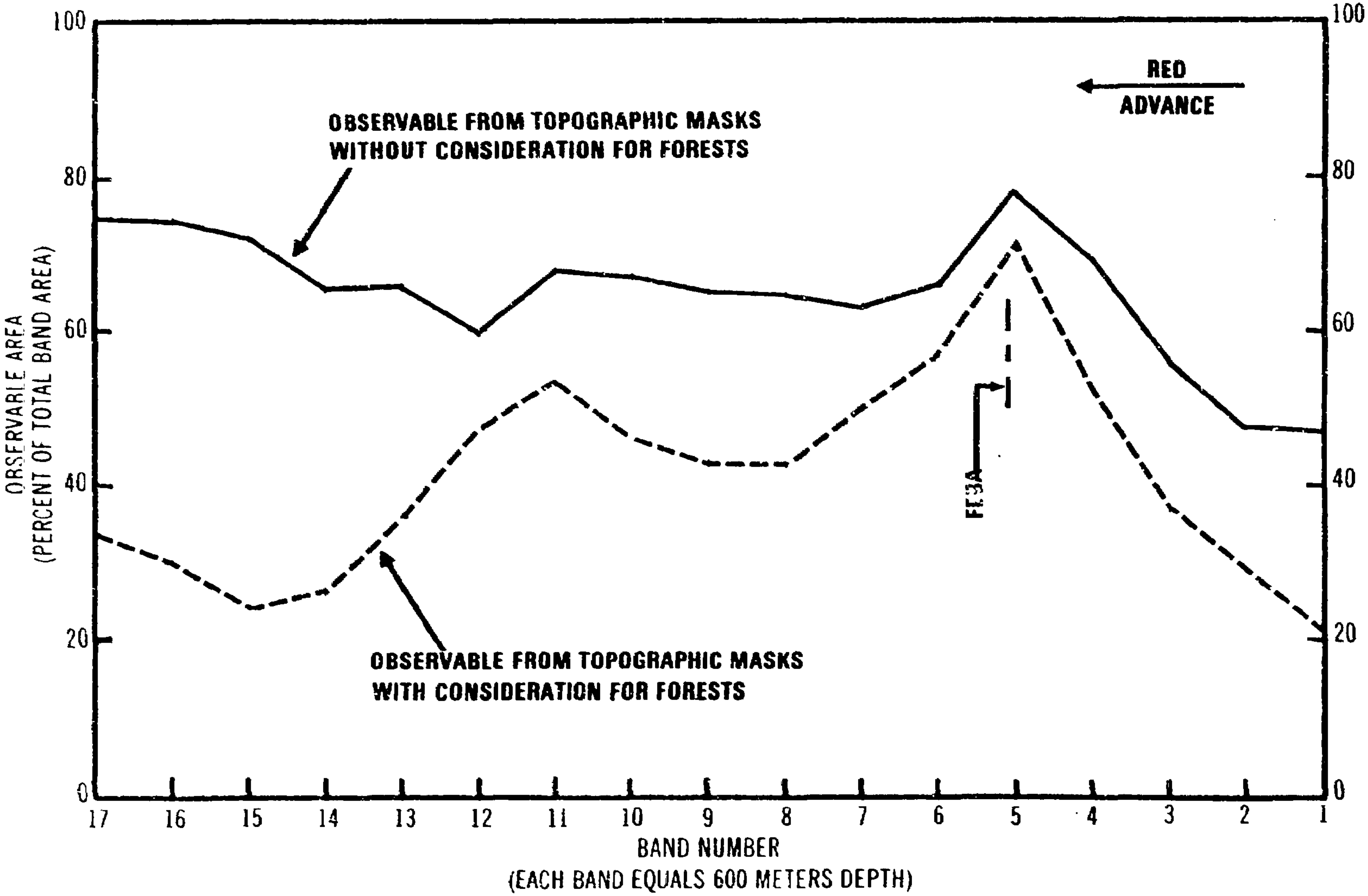


Figure 9

AVERAGE OBSERVABLE AREAS FOR INDIVIDUAL POSITIONS, APPROACHES, AND THE FIRST DEFENSIVE LINE

Approach	Battalion Position Number	Average Observable Areas (Percent of Total Area) Without Forest Effects	With Forest Effects
Bad Hersfeld	2	52.8	36.8
	3	66.4	40.3
	8	62.6	35.4
		60.6a/	37.5
Fulda	1	62.7	38.3
	4	67.1	49.9
	7	56.2	35.5
		62.0	41.2
Meiningen	3	52.1	31.3
	9	80.4	43.4
	11	84.3	54.5
		72.3	43.1
Average for the first defensive line		65.0	40.6

a/ Average of the three positions.

Figure 10

COMPARISON OF POINT-BY-POINT AND CONTINUOUS
SAMPLING OF FRONTAL MASKING

		Fraction of Observable Target Points or Area					
		Without Forest Effects			With Forest Effects		
Approach	Battalion Position No.	Point-by-Point	Continuous	Difference	Point-by-Point	Continuous	Difference
Bad Hersfeld	2	.667	.528	.139	.556	.368	.188
	3	.667	.664	.003	.500	.403	.097
	8	.944	.626	.318	.556	.354	.202
Fulda	1	.611	.627	.016	.556	.383	.173
	4	.667	.671	.004	.444	.499	.055
	7	.556	1	.006	.389	.355	.034
Meiningen	3	.444	.521	.007	.278	.313	.035
	9	.889	.804	.085	.667	.434	.233
	11	.833	.843	.010	.444	.545	.101

Figure 11

As with the topographic area analysis, suitable helicopter firing positions were considered to be located between 2,500 and 3,100 meters from potential target areas. An altitude limitation was imposed that restricted the helicopter from presenting a silhouette against the sky that could be observed from the target. The observable area from each control firing position was estimated by swinging two arcs—one at 3,100 meters and the other at 2,500 meters. Side limits were fixed at the battalion position width extremities. When intermediate forests or hill masses obscured the line-of-sight from a firing position, generated results reflected these reductions.

Successive 600-meter bands were assessed similar to the continuous frontal analysis. Observable areas were determined for each band from each mask category. First, the area observable from firing positions located at the rear edge of forests was determined; then, the additional area increments for each of the remaining mask categories were estimated. Mechanically this was accomplished by placing successively, in descending order of mask quality, map overlays on a mosaic delineating the observable areas generated by the continuous frontal analysis. When a lesser quality mask produced observable area coverage overlapping areas ascribed to higher quality masks, the overlapped areas were disregarded. This procedure resulted in a net increase of 4.7 percent of the total area that could be observed from forests and built-up areas in the Meinengen approach. The Bad Hersfeid and Fulda approaches were not analyzed for forest and built-up area masks; however, a general perusal of these approaches indicated that increases could be expected approximating that estimated for Meiningen.

Summary. The procedures used to extract masking data from topographic maps are straightforward but tedious. Despite this apparent simplicity, data extraction, analysis, and interpretation involve a number of subtleties not the least of which are map constraints, search constraints, and sampling procedures. It was assumed but not confirmed within the ESSG study that topographic maps adequately represent real terrain. The maps searched for masks provide only a two-dimensional representation of real terrain. It was not known how well the maps portrayed the terrain existing at the time the maps were made. Nor was it known how well the maps portrayed terrain as it exists now. No terrain and masking analysis was done "on the ground." The maps provide limited information about covering vegetation; aerial photo-maps were used as an aid in adjusting other data for vegetation effects. Seasonal effects of covering vegetation could not be directly assessed from available maps and other information. Map analysts necessarily worked within all these prior constraints.

The visual search of maps for masks is liable to occasional error or differences in interpretation. At the expenditure of much effort, both errors and differences were very nearly eliminated. However, even carefully prepared data are subject to limitations resulting from analysis using slightly different definitions of admissible masks. For example--the upper and lower limits of permissible helicopter altitude, the dimensions of the search template, and the analyst's notion of facing

forward relative to a target point. Fortunately, it was determined through repeated trials that the study results were not critically sensitive to the possible variance in search technique.

Sampling of areas in the point-by-point method was done within the standard template's "field of view." Many of the same areas (but only battalion defensive positions) were also sampled along continuous potential target lines. The first technique is limited to the usual extent that a small sample can represent an infinite population. The second is potentially in error by limiting its view to the front. The lateral ridges within battalion defensive positions are such however that neither of these sampling errors is as large as they might have been in more general or peculiar terrain. The study has not developed a general figure of helicopter/terrain merit. Almost all the reported results are expressed in the form "fraction of targets lying within range of usable masks." When the results are given for different ranges or different areas, the unavoidable implication is that a higher fraction is a better fraction. The measure is relevant but hardly a sufficient measure of tactical merit. Reverse slopes too steep to be seen reduce the measure but may be so steep that tanks cannot travel them. Mask-like features that are not usable for "pop-up" may, nevertheless, provide valuable helicopter cover. Consequently, the more mask-like features that exist, whether usable or not, the less likelihood of helicopter detection as it executes an ambush.

RATES OF TERRAIN SEARCH BY VISUAL AND OPTICALLY AIDED MEANS

by

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McLean, Virginia

INTRODUCTION

The modeling of ground-to-ground engagements and the air-ground engagement in close air support is heavily dependent, if any meaningful representation is to be made, on the determination of when line of sight between the adversaries occurs, the detection time and other time components comprising the total exposure time of the adversaries. The importance of detection time has been recently acknowledged by the conduct of several major tests in which the measurement of detection time and, in the case of the helicopter, the other time components of total exposure time was the principal data taking objective. The lists of tests is a long one covering ground-to-ground detection under conditions of good[1 2 3] and night[4 5 6] visibility, and air-to-ground[7 8] under conditions of good visibility. Curiously enough, the reports of these tests cited have with one exception[1] (a modeling analysis) not been concerned in either their design or analysis with the fundamental ideas of search theory developed many years ago.[9] Much of the theoretical modeling has been directed toward the concept of detection thresholds and thus has been concerned with target size, range, contrast ratio and lighting levels to the exclusion of the major concern of how long does it take to detect a target when it is fully visible. The net result has been an empericism on the determination of detection times from testing and ecclecticism in its application to war gaming models. The requirement of current GRC simulations to make estimates of the engagement outcomes of the helicopter ground engagement under conditions of day and night, good and bad weather, posed the problem of analyzing the available data under a systematic set of hypotheses in order that inference could be drawn from tests of ground-to-ground target detection concerning air-to-ground detection of targets of a different size and a different level of activity. For example, test results[1] had shown in the ground-to-ground case that moving targets could be detected faster than static targets, yet when moving targets were detected from popping up helicopters various outcomes were observed, either longer times if target coordinates had been given,[7] the same time if they had not[8] or less time every once in a while.[7] It is the purpose of this paper to show how the detection times used in the recent GRC simulations were derived from available data, how they were used, and the evidence of their efficacy in predicting the outcomes of the tests from which they were derived. The fundamental hypothesis of the analysis is that the detection time of ground targets by the air or ground can be predicted from the area to be searched and the rate of search for a target, provided the target is within the threshold of vision.

TEST DATA ANALYZED

A laborious, but certainly not exhaustive, analysis of the recently

available experimental literature has been undertaken. Because of the need for the record of the actual detection time measurements and a sufficient test description for an estimate of the area of uncertainty of the target's location with respect to the observer to be made, only a few of the tests were ammenable to direct analysis. By far the largest and most complete body of data on air-to-ground detections was from two of the extensive USACDEC 43.6[7] series of experiments.* Next in order were the Warren Grove[4] tests, and others by BESRL[5] [6] of night optics, the HumRRO test[3] and finally tests from which certain selective inferences could be drawn such as the Seventh Army Air Cavalry Troop Tests.[8]

The VASE tests consisted of a total of 204 trials in which a COBRA or UH-1B helicopter equipped with one of three different types of stabilized optical sights was tested in the time required to pop-up, detect, and simulate a TOW attack on a target array consisting of a VULCAN and 4 APCs, whose target coordinates had been given to the nearest 1000 meters or the nearest 100 meters in the UMT grid. The helicopter knew its position precisely and the targets were: at either 1, 2 or 3 kilometers; moving or stationary; and in an open or cluttered background. Three helicopter crews were used for each experimental treatment.

The Phase IV trials compared the COBRA (61 trials) and the CHEYENNE (64 trials) in their ability to detect a target consisting of seven vehicles at 4-5 km, (the long range detection), then move to a first engagement at either 2 or 3 km, detect the same target, and finally move to a second engagement position at the same range and repeat the operation. Targets were moving or stationary in either an open or cluttered background. Three different crews were used on each helicopter.

The Seventh Army USAREUR Air Cavalry Troop Tests.[8] These much less well instrumented and nearer free play tests provided estimates of the range at which a variety of distributed ground targets were detected by helicopters using NOE pop-up techniques to search for these targets. The helicopters knew only the general position of the forward edge of the battle area as they engaged in their search for targets. The median range of detection (based on 277 observations) was 285 meters and the mean 570 meters.

The Warren Grove Tests. These extensive tests of the detection time by individuals using the unaided eye, binoculars, and night optics under moonlight, starlight, and part-moon illumination provided information fairly suitable for the inference of the search rates of a single man for a moving and static truck, jeep, and man in the open. The data record is incomplete, however it carefully defined the search area (a 62° fan), the field of view of the optics and the test procedures for the static targets and provided detection probability as a function of range for 30-second search periods. Static targets were always within the field of view of

* USACDEC Experiment 43.6. This experiment consisted of a large number of experiments or tests. Only two, the Visual Acquisition Systems Experiment (VASE) and the Phase IV comparative tests of the COBRA and CHEYENNE made direct measurement of both air-to-ground and ground-to-air detection times of a single helicopter vs a VULCAN AD weapon, several APCs, and tanks.

tripod mounted optical devices, although the range and target type were unknown to the observers. Moving targets (speed not reported) were only indicated to the observer to be within the 62° fan.

Other Sources

Other data resources are referred to to draw certain inferences. Plots of data drawn by Ref 1 from USACDEC Experiment 31.1 of the detection time for a static tank and a static APC and for two moving armored vehicles are the basis for exploring ground-to-ground detection of moving and static vehicles. In this test the area of search must be inferred. Correlative inference (without detailed re-analysis, not possible from the reports) is drawn from work of J. H. Banks, et al, at BESRL[5, 6] and J. A. Caviness, et al, at HumRRO.[3]

Data Reduction Hypotheses

Given that a target of area A is visible under lighting condition l, in a search area (called the area of uncertainty) a_u, the probability of detecting that target within time t, Pd(t) is defined as

$$Pd(t) = 1-e^{-\frac{r_{Abl}}{a_u}t}$$

where: r_{Abl} is defined as the rate of search for the target.

The frequency of detections is then

$$fd(t) = \frac{r_{Abl}}{a_u} e^{-\frac{r_{Abl}}{a_u}t}$$

However, in the real world of human beings no such response is likely on the instant the target area is presented, and there is an appreciable lag in response, particularly for large values of $\frac{r_{Abl}}{a_u}$. In prior related formulations of this problem such as by Bishop and Stollmack[1] the term t_o has been omitted. Tests of the exponentiality of the distribution, such as by Caviness, et al[3], have shown that it was not exponential, but was characterized by a clear cut rise time. For the values of $\frac{r_{Abl}}{a_u}$ that are very small, the effect is probably of very little importance and can be neglected. Thus for large $\frac{r_{Abl}}{a_u}$ the expression is modified to

$$Pd(t) = 1-e^{-\frac{r_{Abl}}{a_u}(t-t_o)} \qquad (1)$$

where t_o is an empirical constant that, like r_{Abl}, must be determined from test data.

For an exponential distribution

$$\frac{r_{Abl}}{a_u} = \frac{1}{(\bar{t} - t_o)} = \frac{.694}{(t_m - t_o)} \tag{2}$$

where $\bar{t}$ = mean of the distribution

t_m = median of the distribution

The scaling rule for r when there is a single element target is

$$r_{A_1 bl_1} = r_{A_2 bl_2} \, (A_1/A_2) \tag{3}$$

No scaling rule on r is attempted for multiple element targets, because, for modeling purposes, the experimental targets for daylight good weather had approximately the same numbers of elements as were being modeled. Scaling of r for the number of observers searching the area of uncertainty is based on an approximation of uncorrelated search,*

$$\frac{r_1}{r_n} = \frac{Pd_1(tmn)}{Pd_n(tmn)} = \frac{Pd_1(tmn)}{0.50} \tag{4}$$

where r_n = rate of uncorrelated search of n observers of an area of uncertainty

$Pd_1(tmn)$ = detection probability of one observer at the median time, tm, of n observers

$Pd_n(tmn)$ = detection probability of n observers at the median time = 0.50

Since all data available are for one or two observers, the result of this assumption amounts to $r_1/r_2 = .586$.

a_u, Air-to-Ground and Ground-to-Ground Search

The area of uncertainty is the area that prior knowledge by the observer bounds the area of search. An observer on the ground usually has a search sector that is bounded in range by line-of-sight considerations. The observers in a popping-up helicopter have a similar problem if there is no prior knowledge of target location. If there is target location information then a_u is defined by sum of the errors of target location, helicopter knowledge of own location at pop-up (navigation error), and the ability of the observers to utilize this information in directing their search. For a stationary target, the area of uncertainty is defined in terms of the CEP of the errors as follows:

$$a_{u\frac{1}{2}} = \pi\,(x^2 + y^2 + z^2) = r(t_m - t_o), \text{ for } R > (x^2 + y^2 + z^2)^{\frac{1}{2}} \tag{5}$$

*Of course if the observers have different assigned areas of search then the problem reduces to the rate of search by the observer over his assigned area.

where $a_{u\frac{1}{2}}$ = The area of uncertainty at Pd (t) = 0.50

x = CEP of navigation
y = CEP of target location
z = CEP of the combined range and angular estimation error of the observers
R = range from observer to the target coordinates

If a median range estimation error of 12% (corresponding to a 17% mean range estimation error) is used then z can be expressed as follows:

$$z^2 = \frac{R^2 \theta_e^{\circ}}{360} \tag{6}$$

where θ_e° = the median bearing estimation error in degrees

If $R < (x^2 + y^2 + z^2)^{\frac{1}{2}}$ then a condition of search over a sector obtains,

and $a_{u\frac{1}{2}} = S\pi(R_m)^2/360$ (7)

where S = the search sector in degrees
R_m = median range of target detection

If the target is moving, a_u has another term dependent upon how much knowledge the observer has of the speed and direction of motion of the target and how "old" the information on target location is at the beginning of search. The general expression is then

$$a_{u\frac{1}{2}} = (x^2 + y^2 + z^2 + d^2),\ R > (x^2 + y^2 + z^2 + d^2)^{\frac{1}{2}} \tag{8}$$

where $d^2 = \left[V_e(t_m + t_n)\right]^2 + \left[R\phi_e\right]^2$

V_e = error in the knowledge of target speed

ϕ_e = error in the knowledge of target direction of motion-radians

t_n = time between the receipt of the target location information and the initiation of search

Estimation of Pd(t)

Following the rationale of Ref 1, N observations of detection (for constant a_u and r) are rank ordered as follows:

$$Pd(t_i) = \frac{i}{N+1} \tag{9}$$

where $Pd(t_i)$ is a best estimate of Pd(t)

i is the rank order of the i^{th} observation

Substituting expression (9) in expression (1)

$$\frac{r_{Abl}}{a_u}(t-t_o) = \ln\left(\frac{N+1}{N-i+1}\right)$$

If the measured detection time, t, is plotted vs $\ln\left(\frac{N+1}{N-i+1}\right)$ and a straight line is fitted to the data, t_o is the value t at $\ln\left(\frac{N+1}{N-i+1}\right) = 0$ and t_m is the value of t at $\ln\left(\frac{N+1}{N-i+1}\right) = .694$. $\bar{t}$ is the value at $\ln\left(\frac{N+1}{N-i+1}\right) = 1$.

Tests of the Air-to-Ground and Ground-to-Ground Search Hypothesis

USACDEC 43.6 Phase IV and VASE Tests. Table 1 is a test of the adequacy of the foregoing hypothesis as applied to the Phase IV tests. In 22 of 24 cases the mean of the absolute value of the differences between the predicted and the experimentally observed values of t_m-t_o is 1.1 seconds. In two cases the result is not explicable in any set of terms and the differences are quite large indeed (29.7 and 7.9 seconds). The fitting was done by sequentially analyzing elements of the 22 cases. To make this data reduction, several characteristics peculiar to this test were used to determine a_u and r, which space does not permit detailing.

The following is a comparison of the VASE Pt 3 test data with the predicted times using the same assumptions for r_o, r_c, θe^o, and V and t_n that were derived from the Phase IV analysis. In all the VASE tests x = 0 and z was estimated for 2000 meters, the mean of the 1, 2, and 3 km over which the data were pooled.

Test	Statistic	Target in open				Target in clutter			
		Stationary		Moving		Stationary		Moving	
VASE Pt 3	N	27.0	9.0	9.0	27.0	9.0	27.0	27.0	9.0
	y meters	19.6	196.0	19.6	196.0	19.6	196.0	19.6	196.0
	z meters	117.0	117.0	117.0	117.0	117.0	117.0	117.0	117.0
	t_m-t_o(meas)	3.0	6.3	4.5	5.6	8.9	13.4	11.7	7.3
	t_m-t_o(calc)	2.6	9.4	5.1	16.9	3.2	11.9	6.5	23.2

The degree of agreement of the VASE tests with the predictive equations is much poorer than that of the Phase IV tests. The reasons probably lie in the pooling of the data that was necessary. Those of the VASE tests were pooled (for N=27) over 3 ranges x 3 fire control systems x 3 crews. For N=9 the data were for the same fire control system as was used in the Phase IV tests but pooled over 3 ranges x 3 crews. That of the Phase IV tests was pooled over 3 crews x 2 ranges for one fire control system. There is the possibility that dust affected the outcome of the VASE tests (run in November and December at HLMR) whereas it did not affect the Phase IV tests run in April at HLMR. Reasonably good agreement (within

Table 1

COMPARISON OF OBSERVED WITH CALCULATED MEDIAN DETECTION TIMES
FOR USACDEC 43.6 PHASE IV

Condition	Helicopter	Own loc error-x m	Tgt loc error-y m	Statistic	Target condition: Open background Static	Open background Mov[b]	Clut background Static	Clut background Mov[b]
Long Range Detection	COBRA	88.5	196	Coordinate search[a]-z-meters	265	265	258	255
				t_m-t_o (Calc)[c] - sec	20.9	39.6	25.7	55.5
				t_m-t_o (Obs) - sec	22.9	36.9	25.5	25.8
				Δ sec	-2.0	+2.7	+0.2	+29.7
	CHEYENNE	99.5	196	Coordinate search[a]-z-meters	0	0	0	0
				t_m-t_o(Calc)[c] - sec	8.7	15.3	11.0	21.1
				t_m-t_o(Obs) - sec	9.4	16.7	15.6	20.1
				Δ sec	-0.7	-1.4	-4.6	+1.0
1st Engagement Detection	COBRA	0	196	Coordinate search[a]-z-meters	153	156	147	153
				t_m-t_o(Calc)[c] - sec	11.1	20.0	13.7	24.7
				t_m-t_o(Obs) - sec	10.7	22.0	13.0	28.0
				Δ sec	+0.4	-2.0	+0.7	-3.3
	CHEYENNE	0	196	Coordinate search[a]-z-meters	0	0	0	0
				t_m-t_o(Calc)[c] - sec	6.9	12.2	8.8	14.7
				t_m-t_o(Obs) - sec	6.9	11.7	9.0	16.3
				Δ sec	0	+0.5	-0.2	-1.6
2nd Engagement Detection	COBRA	0	196	Coordinate search[a]-z-meters	146	145	151	145
				t_m-t_o(Calc)[d] - sec	10.7	12.9	14.0	16.5
				t_m-t_o(Obs) - sec	11.3	5.0	14.0	15.3
				Δ sec	-0.6	+7.9	0	+1.2
	CHEYENNE	0	159	Coordinate search[a]-z-meters	0	0	0	0
				t_m-t_o(Calc)[d] - sec	4.5	5.6	5.8	7.2
				t_m-t_o(Obs) - sec	4.2	5.2	5.5	8.0
				Δ sec	+0.3	+0.4	+0.3	-0.8
All	Both	na		Search Rate - r, m^2/sec	17500		13770	

[a] $z^2 = \bar{R}^2\theta e/360$, where $\theta e = 1.25^o$ and $\bar{R}$ is the average of the four detection ranges associated with each cell.

[b] The target speed was estimated to be 10 mph and t_n = 14 sec.

[c] $t_m-t_o = \dfrac{\pi(x^2+y^2+z^2)+14V(x^2+y^2+z^2)^{\frac{1}{2}}(t_m+t_n)}{r}$

[d] $t_m-t_o = \dfrac{\pi(x^2+y^2+z^2)+1.33V(x^2+y^2+z^2)^{\frac{1}{2}}(t_m+t_n)}{r}$

1.5 seconds) occurred in only 3 of 8 cases. Substantive and unsystematic departures of the observed from the predicted values occurred in five of the eight cases.

Seventh Army Air Cavalry Troop Tests.[8] Most of the targets detected were armored vehicles or groups of armored vehicles. The area in Germany has evergreen forests and the tests were run in March. Thus when a detection occurred, the background could be considered as open. The helicopters were using a NOE doctrine with approximately a 30-second pop-up. Assuming, r_o = 17,500 sq meters per second, the median detection time using expression (7) is

$$t_m = \frac{\pi \times 285^2}{2 \times 17,500} = 7.29 \text{ sec}$$

For this value of t_m, 94% of all detections would have occurred within 30 seconds or less. This inference suggests that the search rate for the Air Cavalry Troop tests in Germany was comparable to that of the USACDEC Phase IV tests at HLMR.

Warren Grove Tests.[4] Table 2 provides a comparison of the detection ranges measured in the Warren Grove tests and the search rate for a 220ft² tank, r_t, inferred from their data using the relation

$$Pd(t) = 1 - e^{-\frac{r_t (A_x/A_t) t}{a_u}} \tag{10}$$

Presented areas of the target were estimated as man 10 ft², jeep 40 ft², and truck 160 ft². The increased ranges of detection with binoculars over the unaided eye are primarily attributable to the experimental procedure, which placed the targets in the field of view of the tripod mounted binoculars. The observer with unaided eye had only the knowledge of the 62° layout of the target field. In fact it appears, on the basis of the rather rough data, that the search rate with binoculars is less than with the unaided eye. Data on moving targets is reported only for 7 × 50 binoculars for a 30 second search under starlight conditions. In this case the field of view was 62°. Unfortunately the tester's hypothesis seemed to be that detections would be made at greater rather than shorter ranges. As a result very few detections were recorded. However, if it is assumed that the search rate for moving targets was the same as for static targets, the result achieved was to be expected. For example, two detections in 16 attempts were made on a moving truck at 770 meters and one detection is predicted. One detection in 17 attempts was achieved at 500 meters and 3 are predicted.

Other Tests. The hypotheses used in reducing the Warren Grove[4] test data are generally confirmed by Banks et al in Refs 5 and 6 where they found that range of detection was increased as the area of search was decreased and that moving targets were detected "equally"[5] in large search areas, but in smaller search areas more moving than stationary targets were detected. It would be of interest to rereduce these data of these two references according to the hypotheses of this paper, however, it would require access to the timing data.

In The Tank Weapon System[1], Fig. 41 provides the detection time data of single ground observers to detect a tank and an APC in daylight at

Table 2

COMPARISON OF DETECTION RANGES AND SEARCH RATES
OF UNAIDED EYE AND BINOCULARS
IN WARREN GROVE TESTS OF STATIONARY TARGETS

	Moonlight			Part Moon			Starlight		
	Truck	Jeep	Man	Truck	Jeep	Man	Truck	Jeep	Man
Estimate pres. area tgt-ft^2	160	40	10	160	40	10	160	40	10
Unaided eye - field of view 62°									
Lite level - Ft. Cdls.	1.45×10^{-2}			2.16×10^{-3}			1.65×10^{-4}		
Pd(50)(m)	510	225	130	430	205	105	320	110	55
7×50 binoculars - field of view 7.23°									
Lite level - Ft. Cdls.	6.62×10^{-3}			2.41×10^{-3}			1.73×10^{-4}		
Pd(50)(m)	950	570	310	900	500	235	700	370	165
Rate of search for 220 ft^2 tank (r_t)-m^2/sec^a									
Unaided eye	4471	3480	4648	3178	2889	3032	1760	832	832
Binoculars	1805	2606	3085	1620	2005	1773	980	1098	874

a

$$Pd(t) = 1 - e^{-\frac{r_t(A_x/A_t)t}{a_u}}$$

for Pd(30) = 0.5

$$a_u = \frac{\pi S}{360}(R)^2$$

$$A_t = 220\ ft^2$$

based on this formulation as an aid in determining what data should be taken and under what conditions it should be measured. Major immediate problems of the authors knowledge are related to air-to-ground tests of target detection time by fixed and rotary wing aircraft under varying conditions of visibility. We at GRC have made estimates of the performance of helicopters using the above formulation, but there is little data on which to base poor visibility estimates. It is strongly believed that a primary, if not the controlling, factor of the choice between fixed and rotary wing aircraft for close air support is that of the range dependency of air-to-ground engagements resulting from target detection time considerations.

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ANALYTICAL SIMULATION OF ATTACKS
INVOLVING HELICOPTER/GUIDED MISSILE SYSTEMS

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I. INTRODUCTION

The implementation of advances in missile guidance technology are reflected in the HELLFIRE missile program-- a program designed to develop a missile to replace the TOW as the helicopter's main anti-armor weapon. As conceived and demonstrated by the U.S. Army Missile Command (MICOM) Research and Development Laboratories, HELLFIRE may have several modes of operation. Data required for an evaluation of the operational utility of HELLFIRE and for comparing it with the TOW have been obtained in various laboratory and field test, and from a series of on-going experiments in the Laser Guided Missile System (LAGUMS) Military Potential Test. Data from these and other sources provide an increasing empirical data base for use in analytical evaluations.

Approximately two years ago, the U.S. Army Materiel Systems Analysis Agency (AMSAA) envisioned the need for a model designed to provide a procedure for combining these data to compare the effectiveness and survivability of the participants involved in a team-on-team engagement. In developing this model special emphasis was to be placed on detailing the unique characteristics of TOW and four modes of operation of HELLFIRE. These four modes are:

- laser homing used with a ground laser locator designator (GLLD),
- laser homing used with an airborne laser locator designator (ALLD) housed in a scout helicopter,
- laser homing with the ALLD housed in the attack helicopter (AH) from which the HELLFIRE is launched (the autonomous mode),
- optical contrast seeker (OCS) homing.

As envisioned, the model would simulate only the duel phase of an engagement in a mid-intensity environment since it was believed that if any one of the several modes was more (or less) effective than any of the others, this information would be most easily discernible in this phase. The model which was subsequently developed has been named HELMATES.

To date the HELMATES model has been used in two efforts. The first, an in-house effort, was a parametric investigation in which simplistic engagement conditions were devised to allow a clear assessment of model sensitivity to input variation.

The second, performed in response to a request from Headquarters, U.S. Army Materiel Command (AMC), was made to provide team-on-team level comparative effectiveness/survivability data in support of the Combat Development Command (CDC) HELLFIRE Cost and Operational effectiveness Analysis (COEA) which in turn was required for the HELLFIRE Army Systems Acquisition Review Council (ASARC).

A description of the HELMATES simulation development to date is the objective of this paper.

II. HELLFIRE MODES OF OPERATION

The modes of operation of TOW and the four HELLFIRE concepts are shown in Figure 1. Digram A illustrates the scout helicopter detecting the target and handing off the target location and activity information to a TOW equipped attack helicopter (AH). The AH must acquire the target, launch the missile and maintain the crosshair of his stabilized sight (all systems have stabilized sights) on the target until missile impact. He then drops behind mask. Tracking equipment on board the AH measures the angle between the line of sight to the target and to the missile position, then generates electrical signals which are transmitted by wire to the control system on board the missile which will direct the missile back to the line of sight.

In the autonomous mode the AH is equipped with HELLFIRE missiles and a laser designator. As with the TOW, the scout detects and hands-off to the AH. The AH must acquire, lase, launch and then track the target till missile impact as shown in diagram B. The missile homes on laser energy reflected from the target. The TOW and autonomous mode HELLFIRE both require the AH to remain exposed until missile impact.

In the remote designation modes shown in diagram C, the scout with ALLD or the forward observer with a GLLD detect, call for the AH, lase and track the target while the AH launches and leaves. The ground designator may be tripod mounted or vehicular mounted. In this mode the exposure time of the AH is reduced considerably, but the designator operator must still remain exposed until impact. The merit of this mode is that the AH need not visually detect the target before launching the missile. This provides for intimate air-to-ground fire support.

A true fire-and-forget capability is provided by the OCS mode depicted in diagram D. In this completely passive mode the missile carries a TV camera and self-contained guidance controls. It homes in on the visual contrast which the target makes with its background. This form of terminal guidance has been employed in the "smart bomb" series in Viet Nam. When the system is activated a TV picture is presented to the pilot and copilot on TV monitors. Also seen on the monitor is a crosshair. The copilot, using a joystick control, uncages the stabilized TV camera and places the target under the crosshair, then engages a "lock-on" switch. The missile control system will identify the center of target contrast as its aim point and, upon launch, generate guidance signals accordingly. Because OCS depends on visual contrast, it is a daytime only system.

Since the aerial platform, the target and the enemy threat are commonality factors with regard to TOW or HELLFIRE employment, it appears quite evident that in a mid-intensity environment where an assault consists of three phases: (1) nap of the earth approach to the well-defined attack area; (2) unmask for the attack, then remask; and (3) nap of the earth return; the second phase, generally referred to as the duel phase, should yield the most revealing information regarding the performance of the alternative concepts. Accordingly, this phase was selected for consideration in the HELMATES development.

III. SIMULATION DESCRIPTION

The essential elements of the duel phase provide the basis for the simulation as shown in the model flow in Figure 2. A scenario whose relevant characteristics could be modified by changing terrain and weather related input data as well as by changing the AH employment concept (the most essential variable) and whose enemy threat and target description are realistic was deemed adequate. The generalized scenario used in the HELLFIRE COEA application, for example, depicted a mid-intensity conflict near Fritzlar, Germany. The attack took place during the daylight hours with good weather prevailing. The selection of a Fritzlar area offered two distinct advantages. First, a digitized terrain model was available from which line-of-sight data had been generated for previous studies. Second, the terrain features of one of the Fritzlar areas were similar to those of an area in the U.S. at which helicopter air-to-ground detection times had been measured.

A tank target defended by an air defense gun, a shoulder fired surface-to-air missile (SAM), and indirect fired artillery represent the maximum threat which can be handled by HELMATES. The threat used in the HELLFIRE COEA application, for example, consisted of the T-62 tank (which was also the target), the ZSU-23-4 with the S-60 as an alternate, and the SAM.

As shown in Figure 2, time plays an important role in the simulation. One time-related essential element is exposure; i.e., intervisibility duration. During the time interval in which a moving tank is exposed to a GLLD operator, for instance, the target must be detected, the AH called in, then as the AH pops up the GLLD operator must designate the target until missile impacts or until the tank enters mask. The AH, after popping up, must detect the reflected laser energy, align the aircraft, launch the missile, then withdraw. If airborne designation is employed, exposure time of the target may be expected to be somewhat longer because of the elevated position of the observer. Helicopter exposure time also varies from one HELLFIRE concept to another. The AH exposure time is expected to be longer, for instance, for the autonomous mode in which designation till impact is required than for the OCS mode in which the AH can withdraw immediately after launch.

The second time-related essential element is responsiveness. Responsiveness is simulated in HELMATES in the form of time intervals separating events. Some examples are:

- break mask to detect,
- detect to lock-on (acquire),
- lock-on to launch (fire),
- station-to-station communication.

Both human hardware responses, measured or estimated, are pre-requisites to carrying out a comparative evaluation and therefore must be contained in the simulation process. The HELMATES simulation provides for handling response time distributions as well as expected values. Relevant response time distributions for the TOW system were obtained for the HELLFIRE COEA application from CDCEC Attack Helicopter Experiment 43.6 conducted at Hunter-Liggett Military Reservation, Fort Ord, CA. Response time distributions for the laser concepts were based on data obtained from 43.6 and from the Laser Guided Missile System (LAGUMS) Military Potential Test (MPT) which was conducted at Hunter-Liggett. Response times distributions for the optical contrast seeker concept were based on data obtained from earlier flight tests of OCS concepts. Likewise, tank time distributions are based on numerous field experiments. Enemy threat capabilities are obtained from the intelligence community. For the COEA application, log normal distributions were fitted to the empirical data by CDC, Ft. Leavenworth for use in the investigation. The HELMATES model has, however, been designed to accept any distribution form.

A third time-related essential element is motion of the participants. The effect of movement on exposure (intervisibility duration) was discussed earlier. Just as important, however, is the ability of the attack helicopter to take evasive maneuvers while exposed; particularly when TOW or the autonomous mode HELLFIRE is employed. Provision is made in the HELMATES simulation for the attack helicopter to perform empirically validated post-launch maneuvers. The evasive maneuvers employed in the COEA application, for instance, were based on information obtained in a lateral maneuver flight test conducted at the Edwards Air Force Flight Test Facility.

Distance represents a fourth essential element which is often time-related. Of great importance is the range-dependent flight time of the missile. Flight time affects the exposure time of the attack helicopter when either TOW or autonomous HELLFIRE is employed. Missile flight time also affects the exposure time of the scout or ground based forward observer when one of the remote designation modes is employed. It is noted that not all distance parameters are time-related. Examples of such parameters are: offset distances between elements of an enemy threat and the maximum launch range of the TOW or the OCS HELLFIRE. (The maximum launch range for TOW is determined by the length of the umbilical wire whereas the maximum launch range of the OCS is a function of the resolution capability of the TV system).

The HELMATES simulation is a Monte Carlo simulation which creates on each replication an event-time history for a specific alternative system. This event-time history is created by sampling from time distributions examples of which are mentioned above.

The two boxes labeled "Time" and "Duel" have been used in the model flow in Figure 2 to represent the simulation steps involved in each HELMATES replication. The last box on this chart, the one labeled "Results," deals with the determination of the relative frequency of occurrence of critical events determined over a fixed number of replications. A more detailed description of the results is given in Section VI "Measures of Effectiveness."

IV. EVENT TIME HISTORY

As stated previously, the HELMATES simulation creates for each specific alternative system an event-time history on each replication by sampling from time-interval distributions. Figure 3 depicts, in terms of the variables, the event-time history for the HELLFIRE laser system when it is used with a ground laser locator designator (GLLD). Similar time charts for the other HELLFIRE options as considered in the HELLFIRE COEA application appear in AMSAA Air Warfare Division Interim Note No. 42, "Application of the HELMATES Model to the HELLFIRE Cost and Operational Effectiveness Analysis, Volume I: HELMATES Engagement Analysis." Only the HELLFIRE (GLLD) time chart is discussed in this section.

As shown in Figure 3, the simulation clock begins at the instant of intervisibility between the ground designator operator (G/D) and the tank target (TK) and is tentatively scheduled to stop at time t_{TD} when the tank will enter mask relative to G/D. (As the simulation advances, however, this "stop" time may be changed.)

The first critical event occurs when G/D detects TK at time t_0. Next, G/D calls for a HELLFIRE laser attack. (HELMATES has been provided with a maximum capability of five links in its communication net.) At time $t_0 + t_{PO}$ the communication link up is completed and the AH begins to break mask. At some time prior to the time the AH reaches altitude the GLLD should be activated. In Figure 3 this time is represented by the time interval Δt_{IL} measured relative to when G/D detects TK. At time $t_0 + t_{PO} + t_3$ the AH will have detected the reflected laser energy (at the end of the first link in t_3) if

- AH is yet surviving,
- G/D is yet surviving,
- TK is yet unmasked,
- neither of two abort rules have been satisfied.*

As soon as the launch takes place AH can seek cover (time interval t_{11}). Maximum exposure time for AH is therefore $t_0 + t_{PO} + t_3 + t_{11}$.

*The abort rules are discussed in Section V "Options."

Particularly important event times occurring during the duel phase of an assault are the times at which a missile is launched, bullets are fired, and a target is hit. That portion of a simulation which deals with exchange of fire is represented in Figure 2 by the box labeled "Duel." The essential elements of the duel requiring simulation are participant effectiveness potential and vulnerability.

Effectiveness potential, as used here, refers to the weapon-related data involved in determining hit probability. Generally, hit probabilities for guided missiles are generated outside effectiveness models. Accordingly, the HELMATES simulation was designed to accept hit probability numbers, for both friendly and enemy guided missiles, which were generated from other sources. Hit probabilities for the guided missiles used in the HELLFIRE COEA were generated at AMSAA.

An air defense gun submodel for generating hit probabilities is included within the HELMATES simulation.* The reason for this is that hit probability is a function of the degree to which the helicopter is maneuvering which in turn is a function of assault time. (The greatest opportunity for an attack helicopter employing TOW to perform evasive maneuvers is during the missile in-flight phase of the attack). The essential air defense gun characteristics employed in the submodel are:

- caliber and type of charge,
- rate of fire,
- bullet velocity,
- tracking errors (bias and random),
- range estimation error,
- ballistic error (round-to-round dispersion),
- slewing and tracking rates,
- fire control time constant.

A more complete description of this submodel is beyond the intended scope of this paper.

Vulnerability, as used here, refers to either vulnerable area data, if the lethal mechanism is a bullet, or probability of kill given a hit data, if the lethal mechanism is a missile. Generally, this information is provided to AMSAA by the Ballistic Research Laboratories (BRL). Accordingly, the HELMATES simulation was designed to accept vulnerability data (in tabular form) from outside sources. The vulnerability data used in the HELLFIRE COEA application was furnished by BRL.

Following the establishement of an event-time history in a HELMATES replication, the probability of success of each event taken in sequence is determined within the HELMATES simulation process. Then, by means of Monte Carlo techniques, each event is declared to be either a success or failure (an attack helicopter, for example, is defeated at some specified instant before launching a HELLFIRE laser missile) and appropriate adjustment, available as options, are made (the remote airborne designator operator, having observed that the attack helicopter could not launch the HELLFIRE laser missile, seeks mask for the scout helicopter).

*also included in AMSAA's EVADE and TRIAD models

Flight time for HELLFIRE is represented in Figure 3 by the symbol t_{FM}. Once the missile has impacted, G/D can take cover (time interval t_{13}). Maximum exposure time for G/D is therefore $t_0 + t_{PO} + t_3 + t_{FM} + t_{13}$.

From Figure 3 it is clear that when $t_0 + t_{PO} + t_3 + t_{FM}$ is greater than t_{TD} the missile cannot reach the tank in time to defeat it. Also as soon as G/D and AH ahve returned to positions behind cover (or are defeated) the HELMATES clock stops even though this may occur at some time before t_{TD}.

In HELMATES, detection of G/D is expected to occur as a result of the designation beam being detected. The TK and possibly the rapid fire weapon (RFW)* are expected to be equipped with laser detection devices. In Figure 3 t_1 is the detection time of G/D by TK relative to the time the designator is activated and t_5 is the time interval elapsing between when TK detects G/D and begins firing. Thereafter TK fires in HELMATES at its average rate.

Two options are available in HELMATES for RFW to begin firing. The first is a result of detection information supplied by TK (time interval t_6) whereas the second follows a separate detection (time interval t_{6A}) and acquisition (time interval t_{6B}) route. Again average rates of fire are employed.

Indirect fire can be initiated by artillery (ARTY) at any time in HELMATES as indicated by the open end of time interval t_7 in Figure 3.

A SAM missile and one air defense gun (AAA) are threats to the AH once it breaks mask. Relative detection time of AH by TK is denoted by t_2; relative acquisition time by t_4. The symbols t_8 and t_9 are used to denote, respectively, relative detection and acquisition times of AH by SAM.

V. OPTIONS

In an attempt to cover some of the "soft data" inadequacies inevitably associated with models at the team-on-team level and above, several options** have been provided within the HELMATES structure. The first group of options deals with planned aborts. Examples are:

- The AH will abort if it does not detect its target within a given time interval, such as 20 seconds.
- The AH will abort if it detects AAA fire before launching its missile.

*Currently, the rapid fire weapon is being simulated as a ZSU-23-4.
** Game rules which may be suspended when desired.

- The AH will abort if the remote designator operator is defeated before missile launch.
- The remote designator operator will abort if the AH is defeated before launch.

The intervals of time for aborts are represented by t_{11} and t_{14} (shown in Figure 3) for the attack and scout helicopters and GLLD operator, respectively.

The second group of options deals with evasive maneuvers. Examples are:

- The AH will perform evasive maneuvers while guiding TOW or HELLFIRE (employed autonomously) to impact.
- The TK will continue on its prescribed path throughout the engagement and will not seek mask as soon as it detects that it is being lased (the time interval t_{12} in Figure 3 is employed when this option is suspended).

The final group of options deals with targets for the enemy threat. Examples are:

- TK fires on either the attack or the scout helicopter, whichever is closer.
- If only one automatic firing gun is available, it will provide air defense (and, specifically, will not attack the GLLD operator).

VI. MEASURES OF EFFECTIVENESS

As previously mentioned, the final step in the HELMATES simulation is the determination of the effectiveness of the HELMATES participants. Primary* measures of effectiveness are:

- probability AH is defeated by each threat,
- probability the scout helicopter (or the GLLD operator) is defeated by each threat.
- probability the missile is launched,
- probability TK is defeated.

These probabilities are obtained, of course, as relative frequencies by the HELMATES Monte Carlo process. An analysis of the sensitivity of these relative frequencies to the number of replications used has been made.

*Expected times of occurrence of critical events and other probabilistic information are also obtained in the HELMATES output.

VII. COMPUTERIZATION

The HELMATES model was designed for the CDC 6600 computer.* Its language is FORTRAN IV. Its core requirement is 110 K words (60 bit words). Execution time, based on the runs made for the HELLFIRE COEA application, varies from 15 to 200 seconds for 800 replications per run.

VIII. SUMMARY

Consideration has been given to the duel phase at the team-on-team level of an AH mission. The HELMATES model has been introduced as an example of the type of simulation which is required for survivability/effectiveness comparison of TOW and HELLFIRE systems at this level. The features of this model are:

- It is designed to accept, as input, data as it is retrieved from field tests such as 43.6 and the LAGUMS Military Potential Test.
- It is sensitive to this input in comparing the survivability/effectiveness across the alternatives.
- It provides an indicator for measuring the limitations of the respective systems in their tactical employment.

*It also has been adapted to the BRLESC computer located at AMSAA.

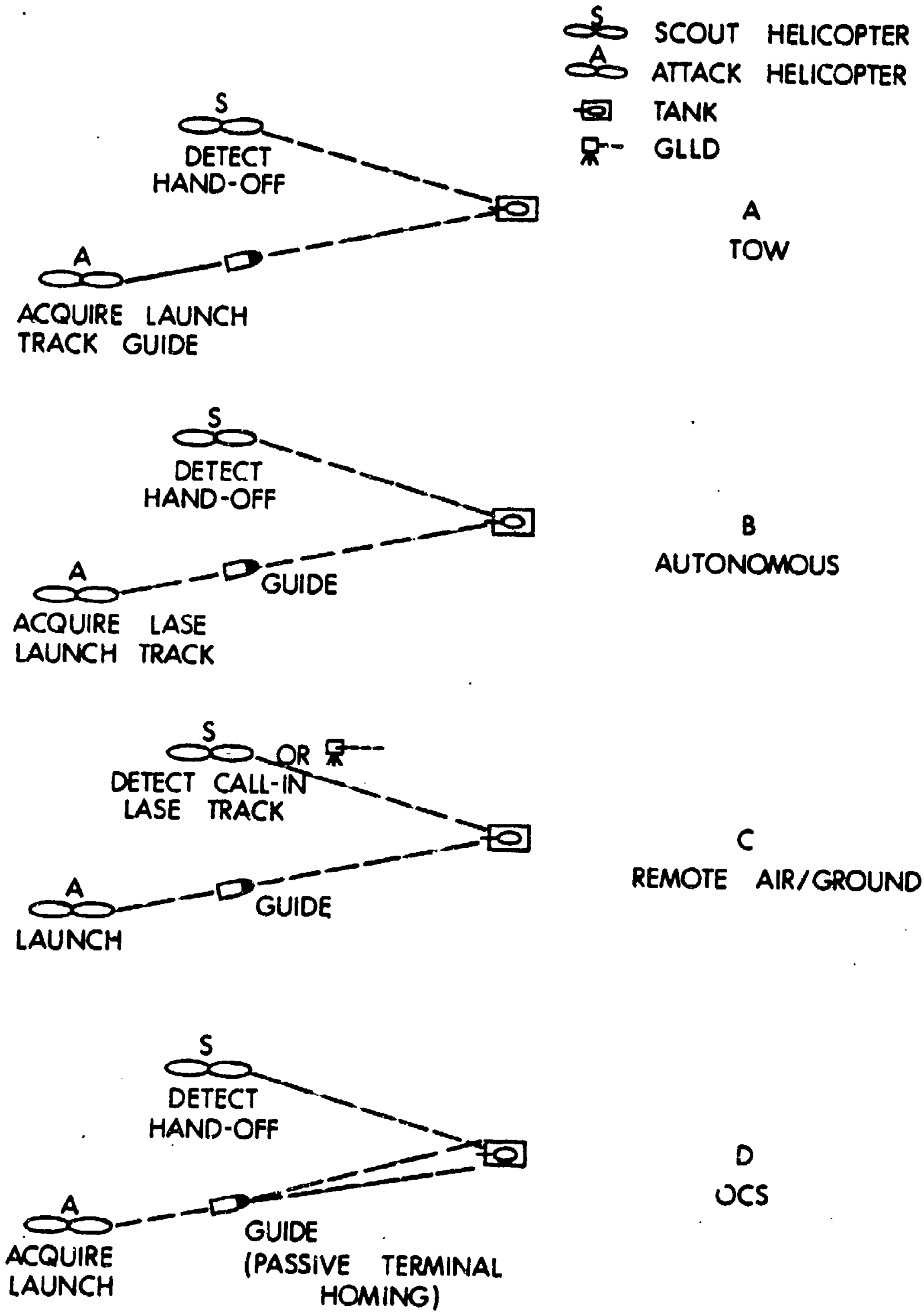

Figure 1. Modes of Operation.

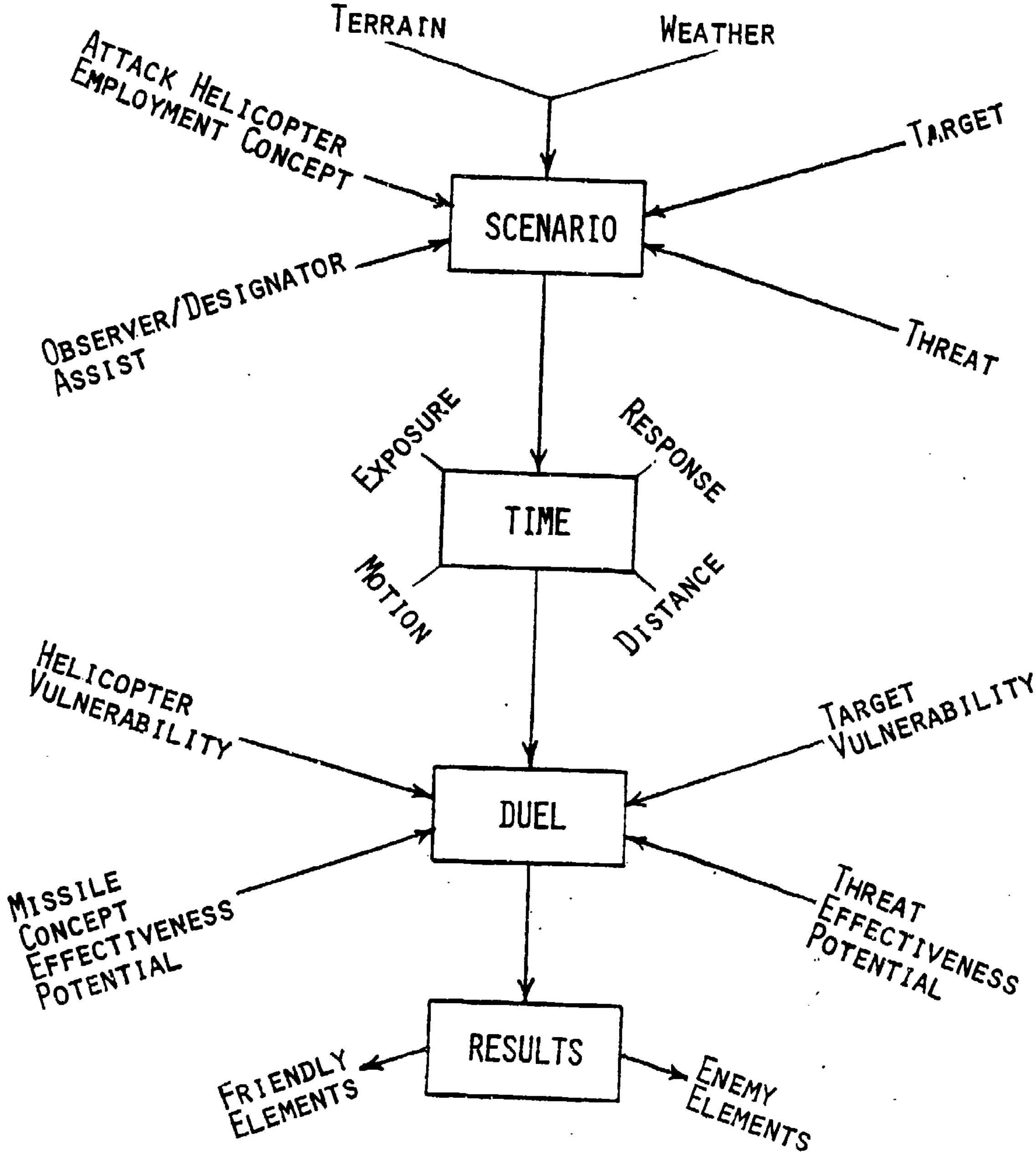

FIGURE 2. MODEL FLOW

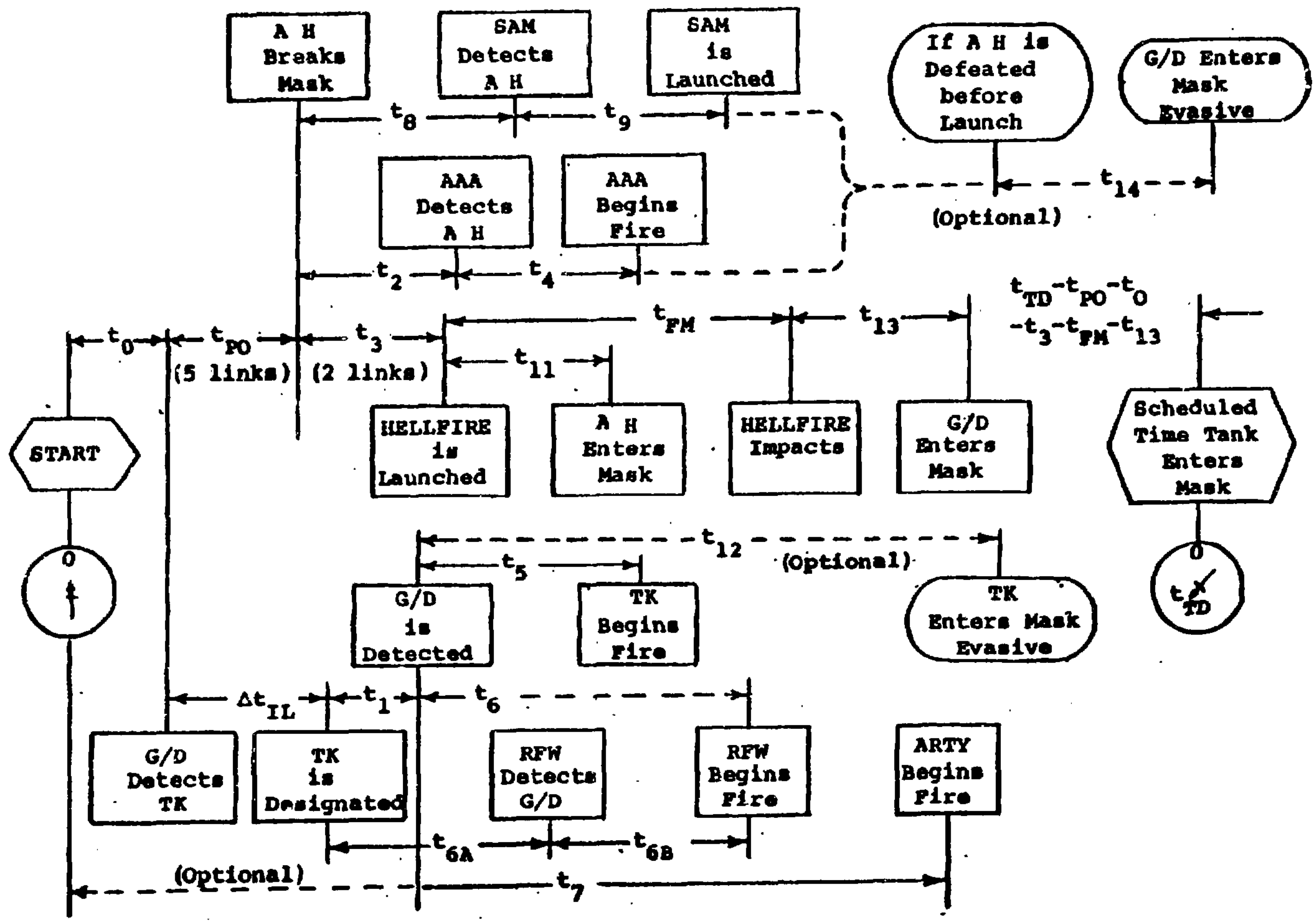

FIGURE 3. TIME CHART FOR HELLFIRE (GLLD)

AD P000606

ANALYTIC MODELS OF AIR CAVALRY COMBAT OPERATIONS

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1.0 INTRODUCTION

This paper describes two analytical models of air cavalry combat operations developed by Vector Research, Incorporated, for the Systems Analysis Group, U.S. Army Combat Developments Command (VRI, 1973). These models were developed to describe the dynamics of combat between attack helicopters and ground elements in two types of engagements: one involving attack helicopters in support of an armored battalion task force engaging an appropriate opponent; and the other, an independent attack of ground elements by attack helicopters. Section 2.0 discusses the independent helicopter attack (IHA) model, and section 3.0 treats the battalion task force models.

2.0 THE MATHEMATICAL MODEL OF INDEPENDENT HELICOPTER ATTACKS

This section describes mathematical models of an independent attack on ground targets by attack helicopters. The models are analytic, rather than simulatory in nature, producing the probabilities of survival of weapons on both sides.

This section is organized into four sections. Section 2.1 describes the military situations, section 2.2 outlines the mathematical model, section 2.3 states the data requirements of the model, and section 2.4 describes the IHA computer program that implements the model.

<u>2.1 The Military Situation</u>: The independent helicopter attack (IHA) model depicts an attack by a Blue attack helicopter unit, acting independently of Blue ground elements, on a Red armored or mechanized formation; a situation which might arise, for instance, in the performance of a screening mission. The scenario treated in this model begins with the attack helicopters at an assault position -- a position where the helicopters deploy before engaging the target forces -- and after the information and command/control elements have made their reconnaissance of the target area and selected firing positions and targets.

Although the model was principally designed for the case in which the helicopters attack in mass, employing mask cresting and standoff techniques, it can be used for cases in which the helicopters employ running fire. In the mask cresting situation for which the model was originally designed, the helicopters emerge from covered positions simultaneously (or as nearly simultaneously as possible) and acquire (or fail to acquire) their targets. They then fire their missiles and remask or fire their cannon for a limited time and then remask. The intelligence and command/control elements then coordinate the continuation of the attack using the same basic tactics. In the running fire situation, the helicopters use cannon only and maneuver while firing. The engagement of firing periods are typically somewhat longer.

There is no basic model limitation on the types of weapon systems which participate, although the model data may be generated by different techniques for different kinds of weapons. The helicopters are assumed to fire at and be fired at by up to nine different groups of weapons, and also to fire at weapons which are not effective against them, and are treated only as targets. The total numbers of weapons is limited only by available computer storage.[1]

2.2 The Mathematical Model: Because of the possible small numbers of attack helicopters (AH's) in operating units, a probabilistic (stochastic) description of the AH combat activity was selected. Accordingly, the model describes the history of the combat activity in terms of the joint probability distribution of all surviving forces (AH and all active ground types) and the fire delivered to other targets. That is, the model is designed to answer the questions: "At time t, what is the probability that there are x_1 AH survivors and x_2 Red survivors from group two, x_3 from group 3, ..., and x_{10} from group 10?" and "Given that at time t there are x_1 AH survivors and x_2 through x_{10} Red survivors from groups 2 through 10, what is the conditional expected amount of AH fire which has been directed at Red targets other than the active weapons in groups 2 through 10?"

The remainder of this section presents the structure of the basic process model.

An analysis of the mask-cresting tactic lead to the model structure, whose features are:

(1) That combat occurs in distinct periods during each of which the behavior of the engaged forces, conditioned upon their surviving strengths, is governed by an identical process, and
(2) That each AH can kill more than one target in a period only with negligible probability.

The first of these features suggested a Markov chain model of the process, and the second was used in determining the form of the transition probabilities. The model structure requires that we generate the single-step transition probability matrix for the Markov chain on the states (x_i). Then, if one can determine the transition matrix, one can generate the survival probabilities at the beginning of each unmasked period from the initial strengths $x_1, \ldots, x_{10}$. Complete, detailed mathematical methods to generate the exact form of the transition probabilities exist, but are not computationally feasible. In this project, approximations to the transition matrix were developed to make computer programming possible. Descriptions of these approximations are given in VRI (1973).

Two items of data were used in developing the transition probabilities:

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[1] Engagements with numbers of weapons significant orders of magnitude greater than 15 might be better treated with the deterministic models described in section 3.0.

(1) the rule for allocating AH's to targets,[1] and

(2) the expected number of opposing weapons which a weapon system can destroy in an exposure period, given they follow the tactics which they would follow in combat, but accomplish no attrition of the firing weapons (this is the total probability of achieving a kill for AH's).[2]

2.3 Data Requirements: The models as programmed in the IHA program require data which is a significant level of abstraction above the basic hardware detail of the weapons. In addition to the initial weapon strengths, the program requires

λ_i = the total expected kills of AH's by a Red weapon of group i in a single exposure period, and

p_i = the total probability of kill for an AH firing at a target in group i.

The λ_i's and p_i's might be estimated from experimental or historical data if it becomes available, but must currently be generated from more basic data which are either measurable or capable of estimation or prediction.

The p_i's may be predicted as a function of simpler probabilities in accordance with the following formula (or any analogy appropriate to a slightly different set of weapon system parameters)

$$p_i = p_A p_L p_F p_K$$

where

p_A is the probability that an AH actually acquires its target in group i within appropriate tactical limits on time and including the effects of range, target visibility, and possible operational failures,

p_L is the probability that an AH can and does launch its ordnance against its target after it acquires it, including all effects of reliability, weather, and operational failures,

p_F is the probability of successful flight (given a launch), of the AH's ordnance, taking all range and other effects into account, and

p_K is the probability that ordnance which flies successfully will kill the target, taking range and other effects into account

[1]And for programming purposes, we have assumed that the rule is a priority rule, identifying target groups in priority order, such that AH's will be assigned on a one AH per target basis in priority order.

[2]This is directly parallel to the attrition rate concept of the differential models in section 3.0 and can be developed in a similar manner.

(this parameter may sometimes be treated as the product of a hitting probability and a kill-given-a-hit probability).

The λ_i's, the expected numbers of passive AH's which a Red weapon can kill in an exposure period, can be determined from any detailed model of weapon performance. Possible methods include the use of the attrition rate models usually associated with the differential combat models or the use of the attrition rate from the air defense gun analytic model presented in Bonder and Farrell (1971). The attrition rate formulae are presented briefly in VRI (1973), and in great depth in Bonder and Farrell (1970).

2.4 The IHA Program: The mathematical models presented in section 2 are implemented by the IHA program. The program accepts an initial force strength vector in terms of the number of AH's and of each Red weapon group from 2 to 10. The Red weapons may be grouped in any way in which each group has a reasonable degree of homogeneity in its performance data and the performance data of the AH's against it. It also reads the p_i's, the λ_i's, a target priority for selection of targets by AH's, and the number of periods for which it is to compute and display results.

The output from the model is a trace of the survival state probability, the expected lethality to passive ground targets, and the mean survivors for each period, up to the maximum the program is to run.

3.0 THE AIRCAV DIFFERENTIAL MODELS

Section 3.0 provides a general description of the AIRCAV differential model programs (VRI, 1973). There are two differential model programs incorporating AH and ADW activities, differing principally in the detailed assumptions and logic of their ground scenarios and the format of their data bases. Both models treat a battalion-level engagement between Red and Blue forces, with Blue forces including attack helicopters in direct support and Red forces including air defense weapons (ADW's). These programs were constructed as modifications of the existing Bonder/IUA differential model programs (Spaulding, 1971) treating ground combat without AH support. The scenarios were therefore constructed as modifications of basic ground combat scenarios.

3.1 Ground Scenario: The ground combat scenarios represent a Blue armored battalion task force, which can be either attacker or defender, in combat with an appropriate Red force. The defending force is deployed in fixed, defilade positions while the opponent conducts the attack along three major axes with up to four predetermined routes of advance per axis. Maneuver weapons on each route consist of tanks and armored personnel carriers, which are supported by long-range and medium-range antitank weapons employed in fixed positions as overwatch weapons. Medium-range antitank weapons are allowed to dismount from maneuvering APC's at point along the attack routes. Defending weapons also consist of tanks, APC's and antitank weapons. Indirect fire from artillery is played for both sides.

A complete description of all movement, terrain line-of-sight, and concealment is taken as input by the programs. The maneuver weapons follow the pre-planned routes in accordance with this description, and may

fire when they are not moving and are inside a range chosen for allowing fire, or if they are moving, have a moving-fire capability, and are within a range chosen for allowing moving fire.

Fire is directed only at targets which have been acquired, with acquisitions occurring as a result of either pinpoint or non-firing detection. Targets are chosen from those which have been acquired in the order of a priority which is fixed throughout the battle and is based on target type and location. For a given round-target combination the accuracy, lethality, and timing of the fire are dependent on such firer-target statuses as velocity, cover, range, etc. The AIRCAV5 model treats two processes not treated in AIRCAV1 - direct-fire suppression and area-effects kills of weapons with exposed crews.

These underlying ground combat scenarios and their detailed assumptions are based on situations developed for use in various studies using the Independent Unit Action (IUA) Monte-Carlo simulation model. The two programs use scenarios and assumptions from different studies which have used the IUA. Specifically, the two programs are

(a) AIRCAV1 which plays the IUA scenarios used in the TATAWS III study (USACDC, 1968), but also uses data from the MBT-70 Producibility/Cost Reduction Study (Battelle, 1969).

(b) AIRCAV5, which plays the scenarios and weapons mixes of the Antitank Weapons Systems Requirements (ATMIX) Study (USACDC, 1970).

The models developed in this program are not Monte-Carlo simulations, but are deterministic analytic models. Although many probabilistic arguments are contained in this formulation, the output of the model is a deterministic trajectory of the surviving numbers of forces.

3.2 Differential Methodology: This section describes the mathematical methodology of the differential models of combat. A detailed discussion of the mathematics of the differential models of combat is given in (Bonder and Farrell, 1970).

For convenience, names are assigned to the numbers of different groups of systems in each force. Let

$m_i(t)$ = the number of surviving Blue units of the i^{th} group at time t ($i = 1,2,\ldots,I$), and

$n_j(t)$ = the number of surviving Red units of the j^{th} group at time t ($j = 1,2,\ldots,J$),

where different groups are determined by their differing abilities to attrit or be attritted by weapon systems of an opposing group. Mathematically, these assumptions take the form of the following coupled sets of differential equations.

$$\frac{dn_j(t)}{dt} = -\sum_{i=1}^{I} A_{ij}(t)m_i(t) \qquad \text{for } j = 1,2,\ldots,J$$

$$\frac{dm_i(t)}{dt} = -\sum_{j=1}^{J} B_{ji}(t)n_j(t) \qquad \text{for } i = 1,2,\ldots,I$$

where

$A_{ij}(t)$ = the utilized per system effectiveness of systems in the i^{th} Blue group against the j^{th} Red group at time t. This is called the Blue attrition coefficient.

$B_{ji}(t)$ = the utilized per system effectiveness of systems in the j^{th} Red group against the i^{th} Blue group at time t. This is called the Red attrition coefficient.

The attrition coefficients (A_{ij} and B_{ji}) are, as one would expect, complex functions of the weapon capabilities, target characteristics, distribution of the targets, allocation procedures for assigning weapons to targets, etc. The model attempts to reflect these complexities by partitioning the total attrition process into three distinct ones:

(1) The effectiveness of weapons systems while firing on live targets,

(2) The allocation procedure of assigning weapons to targets, and

(3) The effect of terrain on limiting the firing activity and on mobility of the systems.

These effects are included in the attrition coefficient as

$$A_{ij}(t) = \alpha_{ij}(t)e_{ij}(t) \qquad [3]$$

$$B_{ji}(t) = \beta_{ji}(t)h_{ji}(t) \qquad [4]$$

where

$\alpha_{ij}(t)$ = the attrition rate, the rate at which an individual system in the i^{th} Blue group destroys j^{th} group Red targets at time t when it is firing at them.

$e_{ij}(t)$ = the <u>allocation factor</u>, the proportion of the i^{th} Blue group systems assigned to fire on the j^{th} group Red targets at time t.

Similar definitions exist for the components of the Red attrition coefficient, B_{ji}.

The methodological basis for calculating the allocation factor, $e_{ij}(t)$, is situation-dependent, since it depends on what assumptions are made concerning target selection doctrines in a given application. The factor not merely reflects target availability, as limited by line-of-sight and acquisition, but also reflects any attempts made by a firer or group of firers to allocate their fire to targets which are in some sense valuable and against which their weapons are effective.

If the stochastic sequence of times between successive kills by a weapon system (against a passive target array) is a renewal process, it has been shown that the appropriate attrition rate for use in the differential models is the reciprocal of the mean time between kills. See Bonder and Farrell (1970) and Barfoot (1969). By definition,

$$\alpha_{ij}(t) \overset{def}{=} \frac{1}{E(T_{ij}|t)}\,, \qquad [5]$$

where $E(T_{ij}|t)$ is the expected time for a single Blue system of the i^{th} group to destroy a passive j^{th} group Red target, given the battle conditions of time t. Formulae for the determination of attrition rates from more elementary weapon system data have been published elsewhere (Bonder and Farrell, 1970) for systems using several firing doctrines.

Sections 3.3 and 3.4 below briefly indicate the nature of the research performed to derive attrition coefficients for attack helicopters and air defense weapons in AIRCAV. Formulae for attrition rates for other systems are given in Bonder and Farrell (1970).

<u>3.3 AH Attrition Coefficients</u>: Earlier, the Blue attrition coefficient, $A_{ij}(t)$, was shown to be the product of an attrition rate and an allocation factor. The purpose of this section is to derive attrition rates for AH's behaving according to the assumptions listed below.

A full list of assumptions concerning the incorporation of AH's and ADW's into the IUA scenarios is given in VRI (1973). The AH attrition rate can be derived from the following three of those assumptions:

(a) Maneuver. AH's will operate independently of each other in their masking and unmasking maneuvers. Coordinated, simultaneous maskings and unmaskings are ruled out.

(b) Target selection. AH's will independently attempt to acquire targets[1] and will fire at the highest priority target found in a fixed period of time (with the priority list and time period as inputs, and the input time period representing the time from mask-cresting to readiness for weapon launch), or if no target has been acquired the AH remasks.

(c) Firing doctrine. AH's will fire only one missle per exposure. Secondary armament is used in burst mode, and a single target is chosen for all rounds until it is killed or the AH remasks.

In the Bonder/IUA (ground weapon-oriented) models the attrition rates of ground weapons are taken to be a function of the weapon systems' statuses and are varied as the cover, velocity, etc. vary. In modeling the AH's attrition of ground targets another approach is taken. In the old approach the various status conditions varied in a complex deterministic manner which could not reasonably be evaluated by any technique but direct computation. In the AH case, the AH statuses vary in a random, but much more foreseeable way, and their variation may be reasonably analyzed before combat computations. For this analysis it is necessary to use AH tactical rules, AH performance data, and terrain maps to generate a description of assault position-to-firing position flight times and times between exposure periods. Accordingly, the AH attrition rates are average attrition rates over the complete AH maneuver pattern.

A detailed mathematical derivation is given in VRI (1973), but the basic approach is to treat AH unmaskings and maskings as an alternating renewal process. The mean time between kills of ground targets follows immediately from this assumption, assumptions (b) and (c), above, and appropriate performance data.

3.4 Attrition of Attack Helicopters: Earlier, the Red attrition coefficient, $B_{ji}(t)$, was defined as the product of an attrition rate and an allocation factor. Whether a Red ground weapon is engaging a Blue helicopter or another ground weapon, the attrition rates and the methodology for allocating firers to targets described previously are also applicable when targets included helicopters. The allocation factor, however, is a function of the probabilities of acquisition against all a firer's target groups, and the algorithm previously used in the differential models for acquisitions between ground weapons is not applicable to calculating the probability of acquiring helicopters that behave according to the modeling assumptions of the AIRCAV models.

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[1] Observation helicopters do not participate in the combat dynamics, but their presence is reflected in acquisition data input for attack helicopters.

Between ground weapons the AIRCAV models treat line-of-sight (LOS) deterministically -- given the coordinates of observor and target the cover status of the target is determined uniquely from an analysis of the terrain. The AH exposure status must be treated probabilistically, however, since the durations of the masked and unmasked intervals are random variables.

Treating AH exposures as an alternating renewal process, the probability a ground observer has a particular AH in an acquired state can be determined (the acquisition process is considered Poisson), and the probability at least one AH in an aggregate is acquired follows directly from the independence assumption, (a). A detailed derivation is given in VRI (1973).

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AD P000607

TOS^2 SIMULATION MODEL

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I. Brief Description of the TOS^2

The TOS^2 is the Operable Segment of the TOS (Tactical Operations System). The TOS is a Management Information System for Tactical Operations of the Army in the field. Its purpose is to assist commanders in the making of tactical decisions in a timely manner. It is expected to provide a secure capability for receiving, processing, storing, retrieving, displaying and disseminating tactical information.

The TOS^2 differs from the TOS in that: (i) the division level is the highest level at which it operates; (ii) it performs functions only in the two areas - FRENSIT (Friendly Unit Situation) and ENSIT (Enemy Situation).

Figure 1 shows the TOS^2 configuration. At the company level, communication to the computer centers is accomplished via DMDs (Digital Message Devices). DMDs are contemplated for use in the TOS^2 as input only devices. At and above battalion level, MIODs (Message Input/Output Devices) are used. Each MIOD includes a keyboard, a CRT display and a printer. At Brigade and Division levels are located GDDs (Group Display Devices), which include an Electronic Tactical Display and a Digital Plotter Map. Each Division has a CCC (Central Computer Center), a DRCC (Division Remote Computer Center) and a BRCC (Brigade RCC). The RCCs link the user I/O Devices with the TOS^2 data base located at the CCC. To model the TOS^2, SAM, a simulation package developed by Applied Data Research, has been used. The next section discusses SAM.

II. Introduction to SAM (System Analysis Machine)

"SAM" refers to the complete simulation package as well as the language used in the package. SAM is a discrete event simulator. This means it is:

a. A next event vs fixed increment type of simulator. This relates to the time-keeping mechanism. SAM uses a future events chain rather than advancing the clock by a fixed increment and checking for event occurence.

b. A discrete vs a statistical (or Monte Carlo) type of simulator. A discrete type steps through tasks in a sequential manner as they would be performed in a "real system". A statistical type aggregates individual events, e.g., it may use mean job time rather than finding the amount of time required for a specific job or job type. The distinction is often one of the level of detail -- in the discrete event simulator you may define mean computation times or mean processing times.

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[3] ____________, *An Introduction to Probability Theory and Its Applications*, Vol.II, Second Edition, John Wiley & Sons, Inc. (1971), pp.468-470

[4] ____________, ibid., p.9

Use of a discrete event simulator is desirable for study of the OS (Operating System) in a multiprogramming environment (which is what we have in TOS^2).

What characteristics of SAM make its use desirable for the modeling of computer systems? It contains:

a. Instructions -- which model the logic of computer programs or software.

b. Declarators -- which are used with instructions to model programs and to describe hardware, I/O files and job processing philosophy of the computer system being studied.

c. A third type of statement contained in SAM is the Directive. Directives control phases in the SAM simulation process. Examples are START-TIME and STOP-TIME.

SAM modularity gives us flexibility; e.g., separate modules are used for hardware, for programs, and for files. Revisions can be made to individual modules without altering the rest of the model.

There are 18 SAM reports available which provide performance statistics appropriate to computer systems.

What can SAM do for us?

a. It can be used to evaluate alternative hardware/software (H/S) configurations -- its modularity is certainly an advantage during such an exercise.

b. System performance under various user loads can be modeled. In many cases, the variation might be examined through changes in parameter settings.

c. It can aid software/hardware design. As in other types of modeling, the design must be thought through in sufficient detail that the system concept is internally consistent, before the whole system can be modeled successfully. A modeling effort can surface inadequate intermeshing to components that may otherwise go undetected until final design stages. In addition, SAM can be used to evaluate the realism of specification requirements.

d. It can be used to study the effects of alternative system policies.

SAM is not the only simulation package available which would be suitable for the effort discussed here. Others which were considered include IBM's CSS and Rand Corporation's ECSS. The SAM package was selected because it appeared to meet the requirements of the task and the US Army Computer Systems Command had already built a SAM model of TOS^2 which could be utilized as a baseline. The USACSC version (called Version I of the TOS^2 model) is discussed in the next section. CSS was not chosen because no significant advantages were found and because of cost. ECSS was not chosen because it has only recently been developed

and at the time our effort began, an exportable version was not yet available.

III. Version I of the Model

Version I of the TOS^2 model was developed by the US Army Computer Systems Command as part of the TOS^2 system engineering study. A description of the model is presented in reference 1. The primary intent and result of the USACSC TOS^2 simulation effort was to demonstrate the capability of modeling TOS^2 in a manner which could prove beneficial to the design and development of the system.

A. Assumptions

In order to develop the Version I model while the system specifications were still in a state of flux, the USACSC simulation team made assumptions and simplifications necessary for implementation of a model. Consequently, the model and the finalized system specifications do not agree. The assumptions fall into three broad categories - user (system load), hardware and software.

The user interface and system load was postulated based on the results of previous studies and bread board systems. The system user input rates were taken from demonstrated results of the TACFIRE system. The system load was extracted in part from the DEVTOS program. The characteristics of the TOS^2 hardware were derived from currently available items and in some instances, simplified to speed upthe modeling effort. For example, core size was not constrained in order to evaluate the maximum amount of core required to keep the system functioning. However, this does prevent the evaluation of through put time due to core contention by programs. The Random Access Memory (drum storage) was postulated as one large unit as opposed to the actual number of units. This was done for ease of modeling as the model of a multi-drum system would be very detailed. The TOS software was also extrapolated from the previous TOS efforts and other systems. Instruction sizes for programs were derived from DEVTOS and TACFIRE systems. A very simple processing scheme was initiated without any associated job priority scheme.

A number of other assumptions and simplifications were made to facilitate rapid model development. However, an exhaustive discussion of these would serve little useful purpose here.

B. Results

The initial model provided insight into areas requiring further definition in the TOS^2 system and contributed to redirection of the modeling effort. The model has been used in the evaluation of an initial estimate of the system message load in the normal and peak message traffic environments. It has helped to quantify the supposition that the slow operator input rate due to input devices will handicap the system.

1 "The SAM Model of the Field TOS Computer System - Version I," USACSC, Fort Belvoir, VA, 27 Feb 72.

The model has indicated that the CPUs will not be utilized optimally as a result of the "I/O Bound" characteristic of the system. Although the model contains a greatly simplified version of the evolving software design, it has been beneficial in that it pinpoints areas which require more study.

As a result of the initial modeling effort, an updated model of the TOS^2 system is being developed. On the initial update, most emphasis is being placed on the man-machine interface. Operator interaction with the system is being investigated and incorporated. The updated version is described in the next section.

IV. Summer of 73 Version

A. Summary of Model Changes

In this version of the model we have updated Version I by:

- Incorporating equipment changes -- it is a much more realistic representation of MIODs and DMDs.
- Implementing shared communication channels.
- Changing the message loads -- it contains the loads resulting from ECP 1002.
- Implementing message priority processing.
- Revising the OS to accomodate the above updates.
- Optimizing the SAM doding.

Some details of these changes are given in Section C. Section B specifies the uses to which the model will be put which require the above updates. Section D gives assumptions and simplifications which apply to this version of the model.

Figure 2 shows the portion of the model which is being updated.

B. Purpose of the Model

The updates described in this paper are designed so that the new version can be used for:

- Analyzing message loading to answer questions like -- How much of a bottleneck is the MIOD keying rate? Where is the system capability greater than is necessary? How does the priority handling scheme affect message processing times? How sensitive are message waiting times to the message loading?
- Studying hardware changes.
- Studying the baseline communications channel configuration -- Traffic analyses have been performed on the TOS^2 communication channels but they have not taken explicit account of interactions. What waiting times will be associated with communications?

. Studying the effects of output interrupts on input message composition.

. Determining the impact of channel acquisition priorities. How does system response time vary as channel acquisition priority is varied between input and output?

Since this version of the model was built utilizing various assumptions and simplifications, it cannot be used to answer any and all questions that one might expect a hardware/software model to answer. In fact, once the model is running, it may be found that some of the items listed in the paragraph above cannot be satisfactorily analyzed until additional details are put into the model. That comment leads us to another use of the model -- the identification of refinements needed in the model in order that specific problems can be addressed. The next section gives details of modifications in this version of the model.

C. Details of the Modifications

1. Communication Channels

TOS[2] Communication Channels between DRCCs and the input/output devices, and between BRCCs and devices are represented in Figures 3 and 4, respectively. All channels to input/output devices are half-duplex, and as many as five devices may share the same channel. Transmission overhead varies by device location and delays due to voice competition may be included. The channel representation in the model is shown in Figure 5. Input messages waiting are stored in INP-CHAN-Qs while output messages waiting are maintained in a separate set of queues, OTP-BUFF-Qs.

2. Message Generation

Figure 6 shows the logic used in message generation. There is a different mean message load used for each input device. A Poisson arrival time is assumed. Using the message loading data, a selection of message type is made by choosing a random number which is transformed into a message type through a loading percentage table. Characteristics for each message type are read in at simulation time.

3. Message Input/Output Logic

The DMDs, MIODs and the communication channels are modeled in SAM with activities under the control of a dummy CPU (CPU4). This is necessary for modeling activities external to the computer system. Each time an "event" occurs, CPU4 is interrupted. An "event" represents the start or end point of modeled message handling activities. The events of interest are given below:

Events

a. Input Message Arrival
b. End of Operator Activity
   (1) Input Message (First Entry)
   (2) Review Message (Hierarchical Review)
   (3) Error Message (Edit/Validation)

(4) Message Request to RCCs (Accept Output)
(5) Output Message (Read Only)

c. End of Transmission
(1) RCC Acknowledgment (Input Message Receipt)
(2) RCC Output Message
(3) RCC Sense Message (Notification of Output Message)
(4) RCC Notification that Device Channel is Free (Artificial Transmission)

CPU4 logic flow charts and further details of the modifications are given in reference 2.

D. Assumptions and Simplifications

1. The Message Input/Output Device Logic

MIOD capabilities have been simplified. Significant features of the MIOD equipment are represented in the model as follows:

a. MIOD operators are notified of output messages routed to the Display Editor (DE) screen. This output notification consists of a Sense Message from the RCC. The operator accepts output for the DE by returning a Message Request.

b. Output messages routed to the Electronic Line Printer (ELP) are transmitted without operator intervention.

c. Since output may be lost or degraded if the cursor is not reset, the operator must decide on the disposition of messages in progress when he is notified of output for the DE. It is assumed that the operator will not interrupt review, reading or correction of messages to accept output. However, the model allows input messages of lower priority than the waiting output to be interrupted to accept output. This interruption will cause any partial composition to be lost and the message will have to be keyed again. Precedence categories allowed to interrupt input composition may be varied so that input composition is never interrupted to accept output or is always interrupted. Input message composition is never interrupted for other input messages.

The only message traffic represented on the communications channels is operational messages and the sense and message requests for messages routed to the DE.

2. Communications

It is assumed that a Message Request (MREQ) is followed by the output requested. The channel is not subject to seizure prior to output transmission.

The sense message to a MIOD may not be immediately followed by a MREQ. Even when the message at a MIOD is disposed of and output is waiting, there is a lag (due to human reaction time) which may allow a MIOD input message to intervene. For example, human reaction time to press a button for MREQ transmission may be on the order of 2.5 seconds, while net acquisition dropouts are likely to be .5 seconds and up in steps of 1 second

[2] "TOS2 SAM Simulation Model: Summer of 73 Version," USAECOM, Fort Monmouth, NJ To be Published

V. Closing Comments

The designer of a complex system could determine an optimal design if he could examine the performance of all possible designs for the system. This, of course, is never possible. In practice, the other extreme is often attained - the performance of alternative system designs is not examined. Estimates may be made for the relationships between known subsystem characteristics and performance of the overall system but until all subsystems are tied together, system performance is usually very much unknown.

Simulation can be used to give better estimates of system performance. However, many large systems have been designed without the use of simulation. Others have used simulation, but not very successfully. Successful uses of simulation in design are claimed for the AF Advanced Airborne Command Post and for the FAA 920 System.

Design decisions in the TOS^2 program (especially in software development) are being made without the help of simulation. We expect that an important contribution of our simulation effort will be for the future versions of TOS. Design of the TOS will benefit greatly from use of a simulation model which will be based on experience gained with TOS^2.

The TOS^2 model will also be utilized as a basis for systems effectiveness evaluations during TOS Concept Development. Hardware and software tradeoffs may be evaluated for their effects on message processing times. Different hardware/software configurations may be modeled as an extension of the present model. The resulting processing times may then be evaluated for effectiveness considerations.

Downstream it is expected that the SAM package will prove to be of great value in modeling other computer systems. After TOS^2, TOS I is the next step. These two systems are basically file systems. TOS IV is expected to have more sophisticated capabilities; e.g., it will recommend preferred courses of action to the decision maker. Not only can SAM be used to model the TOS throughout this development from TOS^2 to TOS IV but it also might be used to model an expanded environment where the TOS is interconnected with other tactical ADP systems; e.g., REMBASS, ATMAC and TACFIRE.

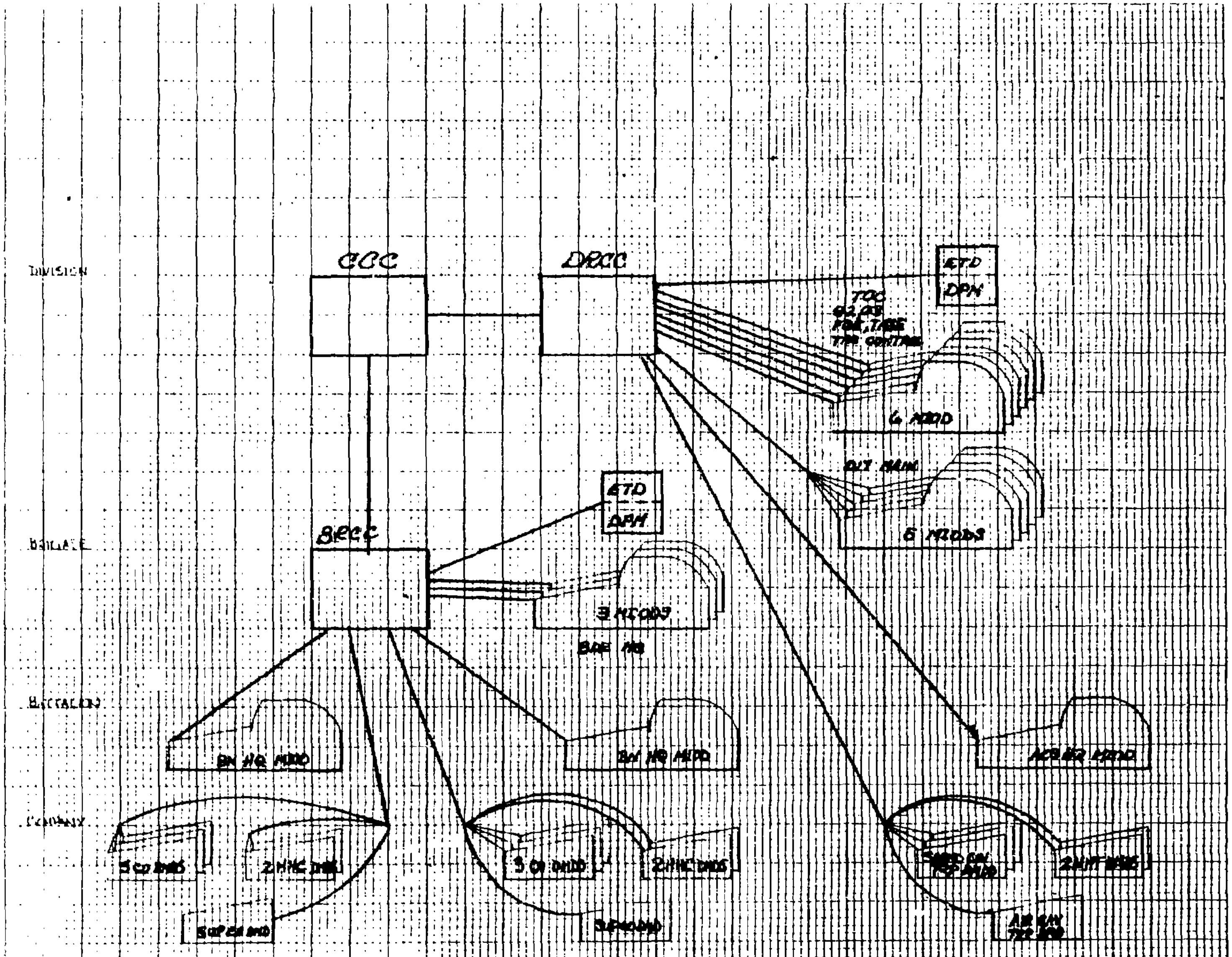


FIGURE 1. TOS² DEVICES AND COMMUNICATION LINKS

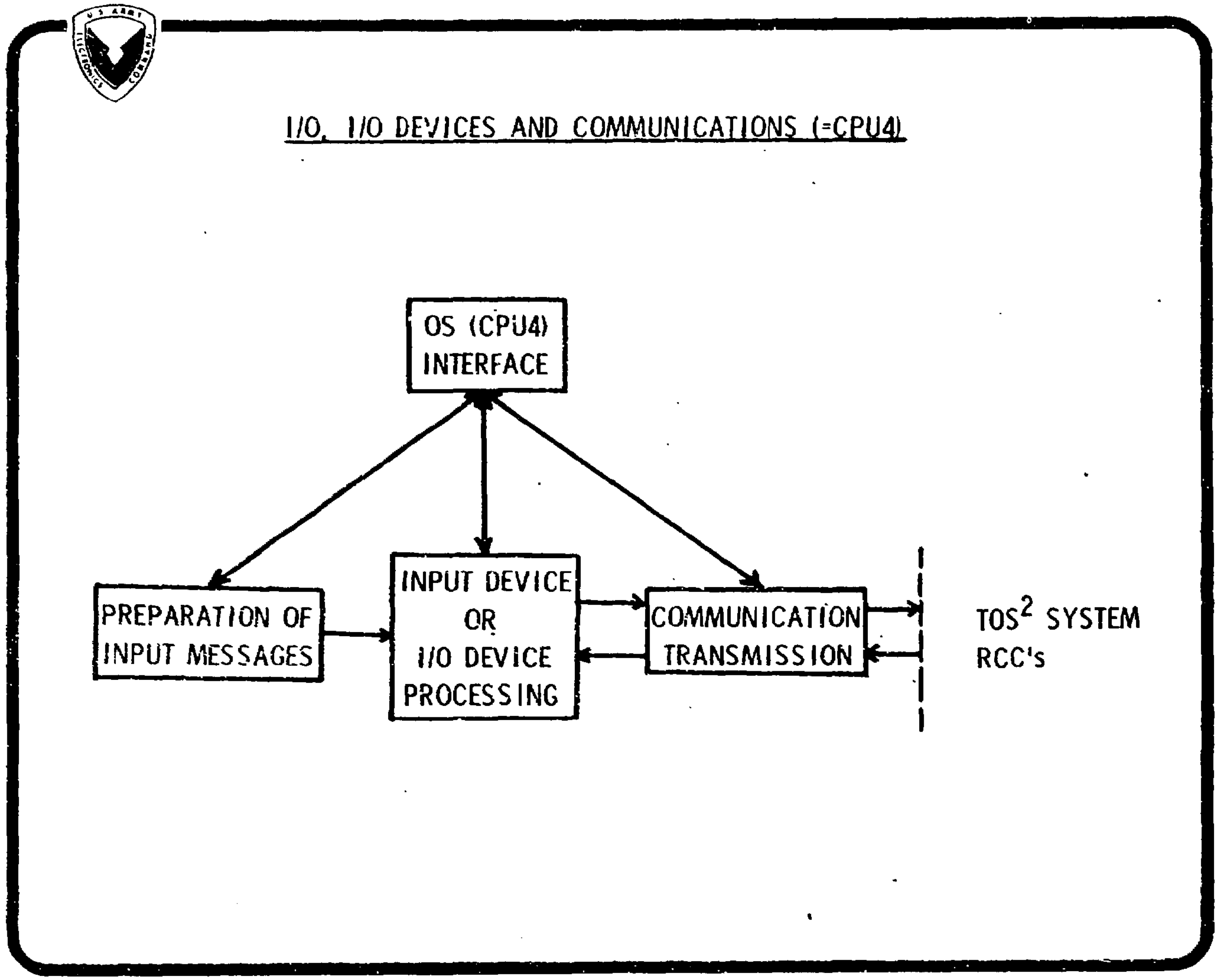
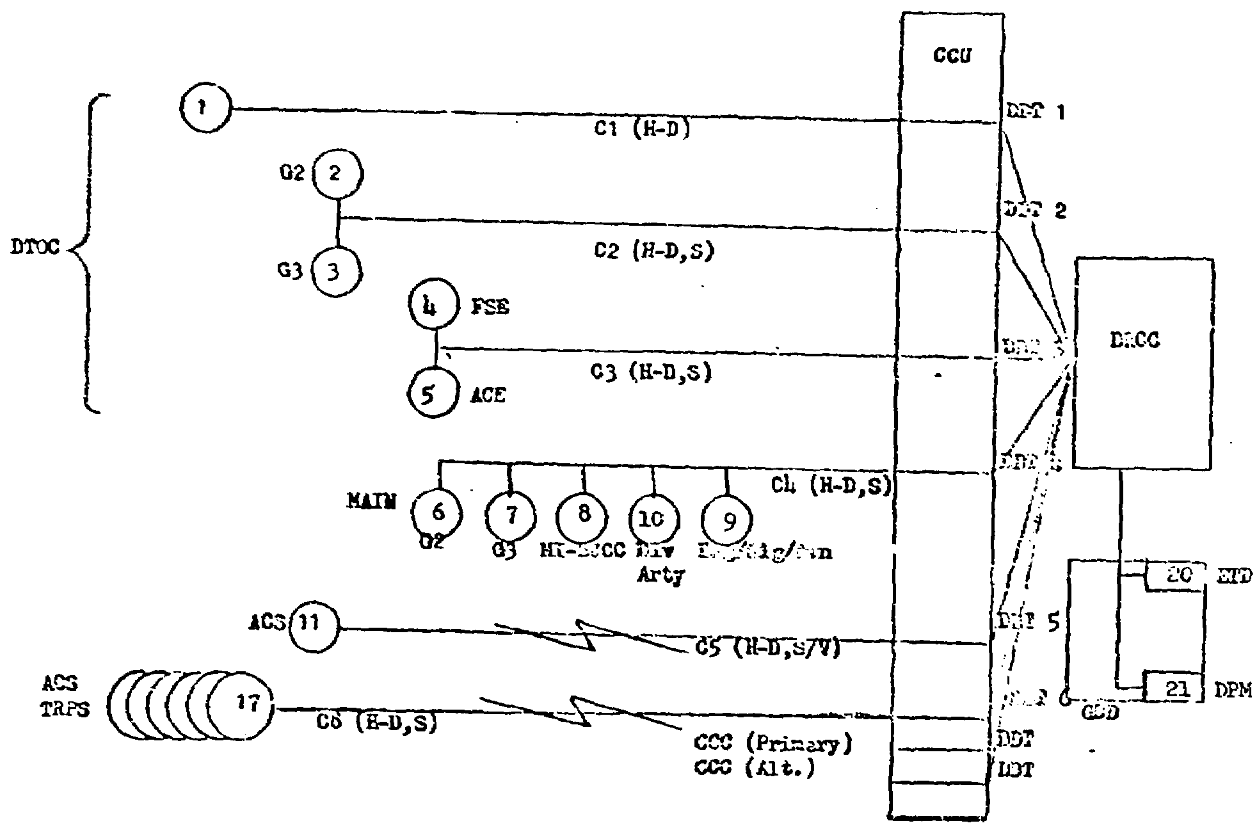


FIGURE 2

SEL FORM 1 SEP 68 1105A

ESC-FM 3330A-68



The inclosed numbers are the device numbers used in the Simulation.

MIODs

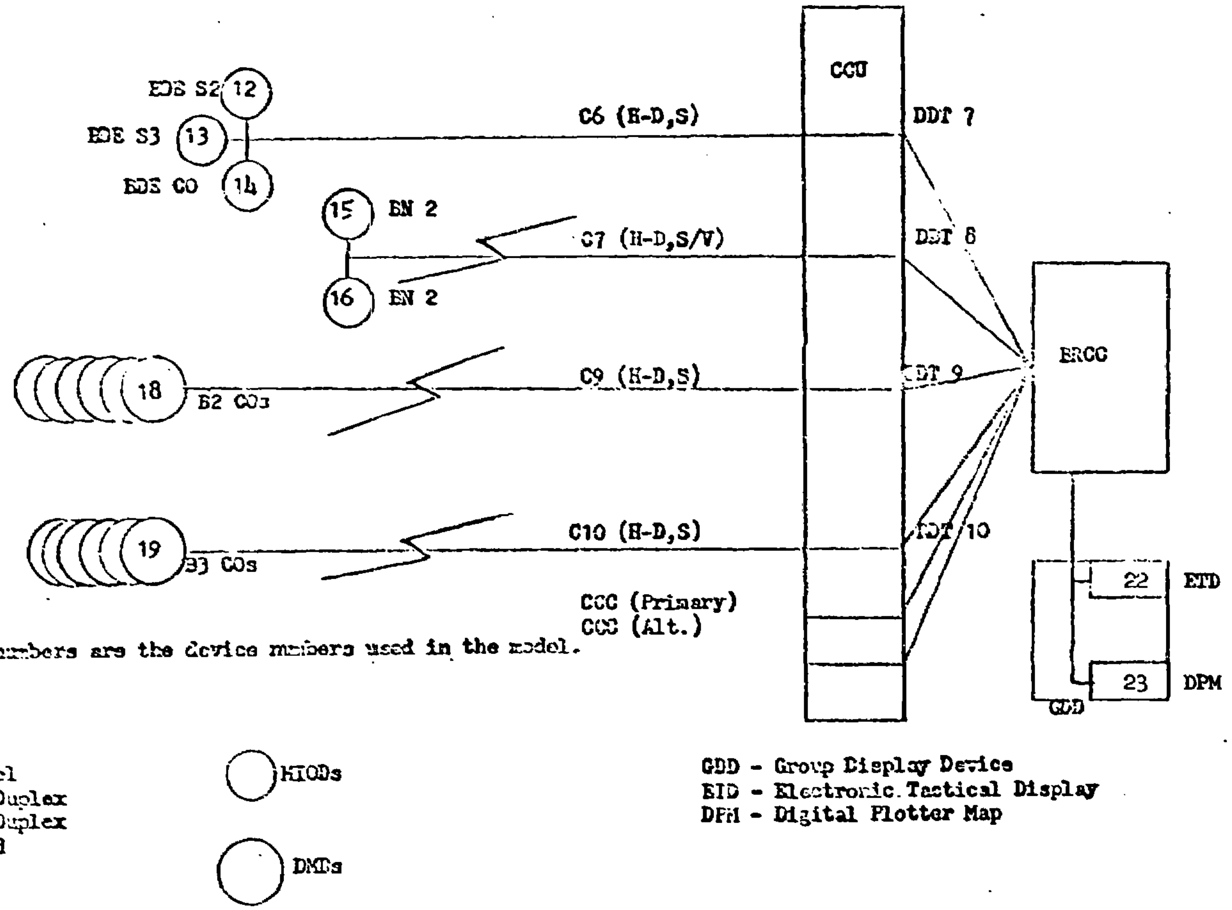
DMDs

C - Channel
H-D - Half-Duplex
S - Shared
V - Voice

GDD - Group Display Device
ETD - Electronic Tactical Display
DPM - Digital Plotter Map

CHANNEL CONFIGURATION
DRCC INPUT DEVICES

FIGURE 3



The inclosed numbers are the device numbers used in the model.

C - Channel
H-D - Half-Duplex
F-D - Full-Duplex
S - Shared
V - Voice

GDD - Group Display Device
EID - Electronic Tactical Display
DPM - Digital Plotter Map

CHANNEL CONFIGURATION
ERCC INPUT DEVICES

FIGURE 4

CHANNEL REPRESENTATION 1 June 1973

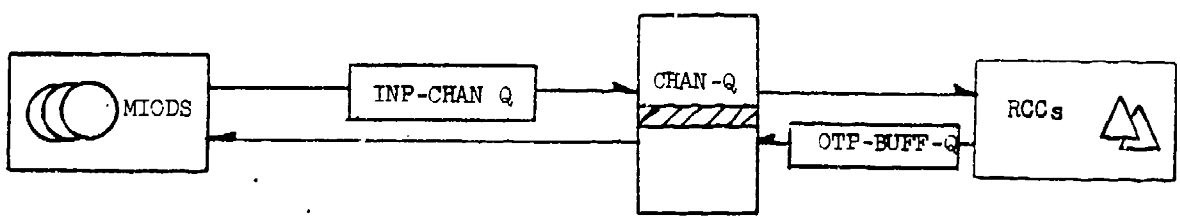


Figure 5

PREPARATION OF
INPUT MESSAGES

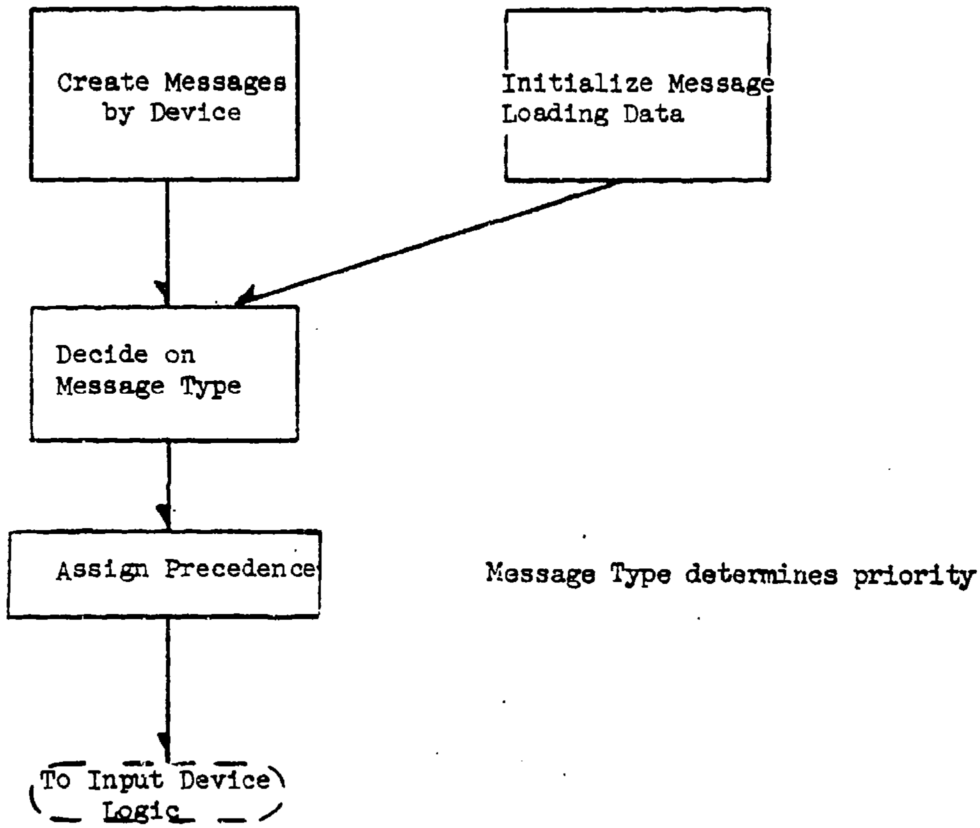


Figure 6

Detection in the Presence of Nonuniform, Mixed Suppressive Fires

Timothy J. Horrigan
Horrigan Analytics

Suppression, as a concept, is given a simple operational explication through a 'single-round period of suppressive effect' which is associated with each projectile impacting in the vicinity of a combatant. During each such single-round period of suppressive effect, which commences at an indicator instant, the affected combatant is *suppressed*; at all other times the combatant is *unsuppressed*. A *period of suppression* for a combatant that is unsuppressed begins with an impact that produces a nonzero, single-round period of suppressive effect; and it ends when the affected combatant first thereafter becomes unsuppressed. Artibrarily long random periods of suppression for the affected combatant may thus arise from overlap between consecutive single-round periods of suppressive effect.

By proceeding from this definition, expected durations of periods of suppression are deduced under very general conditions for situations in which the impact times of the associated projectiles are adequately represented by independent Poisson processes with constant intensities. The resulting model is mathematically exact, and it includes:

- Arbitrary, random durations for individual single-round periods of suppressive effect that stochastically depend on the miss-distance of the associated projectile
- An arbitrary number of different, nonuniform impact distributions for each type of projectile
- Different distributional characteristics for the single-round period of suppressive effect associated with each distinct pair of projectile-target types

The formulas which result are remarkably simple; they depend only on the average durations of the random single-round periods of suppressive effect and the average arrival rates for the associated rounds. Expected detection times for search processes in which the search activity is suspended during periods of suppression retain the same simplicity.

In those situations the expected durations of a period of suppression and of a period to a detection grow exponentially both with the rates at which projectiles impact and with the average durations of the probabilistically different, single-round periods of suppressive effect. When the detection rate during suppression is small but not identically zero, the corresponding expected detection times can be much smaller than what they are when that rate is identically zero. Indeed, they can become sufficiently small to make all-or-nothing representations of suppressive effect unsatisfactory for many typical applications. Fractional suppression, a more satisfactory concept, is introduced to accommodate nonzero activity rates during suppression.

SUPPRESSION AT ITS SIMPLEST

Suppression is initially idealized herein as a hiatus introduced into a combatant's activity by the nearby impact of a round. Such a hiatus, when associated with a single round, is defined to start at the time of the impact or other indicator and to continue for a positive duration thereafter. It is termed a *single-round period of suppressive effect*; 'volley' or 'burst' may, of course, be substituted for 'round' when appropriate.

The duration of a single-round period of suppressive effect is inherently voluntary and accordingly may vary widely from combatant to combatant and even from one combatant at a given time to that same combatant at another time. Miss-distance, environment, and round type are additional important sources of variations. However, because the duration is voluntary, speaking of a constant duration is meaningful notwithstanding what may be its actual, probably great variation from instance to instance.

So long as all inter-round impact times exceed the duration of a single-round period of suppressive effect, the total time during which a combatant is suppressed is defined to be the sum of the individual durations. When additional rounds impact during an existing period of suppressive effect, that period will be prolonged, at least until cessation of the single-round period of suppressive effect associated with the last of the additional rounds. A period of suppression for a combatant is consequently defined to terminate when an inter-impact time first exceeds the duration of a single-round period of suppressive effect. The discipline thus prescribed for the idealized combatant is that its combat activities are to be resumed at the expiration of the single-round period of suppressive effect associated with the last impact in its proximity.

Together these concepts determine a nearly irreducibly simple mathematical model of suppression. It requires only

- a region of suppressive affect associated with each combatant
- a constant duration τ for the single-round period of suppressive effect caused by an impact in the affect region
- a Poisson process $N^*(t)$ with constant intensity λ for the impact stream within the affect region

so that λ and τ, two parameters, alone need quantification. $N^*(t)$ is of course the impact point process, the number of impacts in the affect region in a duration t. Define S^* to be the random duration of a period of suppression.

Without loss of generality the combatant may be assumed initially to be suppressed by an impact in its region of suppressive affect at time zero. It will thus remain suppressed at least until τ ; whether it continues to

be suppressed at some time t depends on whether an appropriate number of timely additional impacts occur. On the hypothesis that $N^*(t) = n$, the impact times of the n rounds in the affect region are uniformly and independently distributed on the interval $[0,t]$ because $N^*(t)$ is Poisson. If T_i^* for i = 1, 2, ..., n respectively designate the random inter-impact times for those rounds, and if T_{n+1}^* is the duration between the last impact and t , it follows from a theorem[1] of De Finetti that

$$\Pr\{\bigwedge_{1}^{n+1} T_i^*>t_i\} = (1-\frac{1}{t}\sum_{1}^{n+1} t_i)_+^n$$

when $(x)_+$ designates the positive part of x : $(x)_+ = 0$ for $x<0$, and $(x)_+ = x$ otherwise. By virtue of an identity[2] for the realization of none out of m events (with $m = n+1$) , the probability that all the T_i^* are equal to or less than τ is:

$$\Pr\{\bigwedge_{1}^{n+1} T_i^*\leq\tau\} = \sum_{0}^{n+1} {}_k\binom{n+1}{k}(-1)^k(1-k\tau/t)_+^n .$$

Since the duration S^* of the period of suppression exceeds t if and only if all the T_i^* are equal to or less than τ , it follows that the right member of the preceeding equation is in fact $\Pr\{S^*>t|N^*(t) = n\}$. Therefore, the unconditional probability that $S^*>t$ is

$$\Pr\{S^*>t\} = \sum_{0}^{\infty} {}_k (-1)^k[\lambda(t-k\tau)_+]^{k-1}\left[\frac{\lambda(t-k\tau)_++k}{\underline{|k}}\right]e^{-\lambda[t-(t-k\tau)_+]}$$

after the resultant order of summations is exchanged and the inner extended summation is put into closed form.

The right member of this equation is not convenient for the determination of the expected value of S^* or its variance. Its Laplace transform, however, is both convenient and intrinsically useful, as later considerations will illustrate. Let $\mathcal{L}$ be the Laplace transformation operator, and let s be the transform variable. Termwise application of the fundamental transformation

for powers of t , which may be written

$$\pounds(t^{m-1}/\underline{|m-1}) = s^{-m}$$

for positive, integral m , together with the shift theorem yields

$$\pounds[\Pr\{S^*>t\}] = [1-e^{-(\lambda+s)\tau}]/[s+\lambda e^{-(\lambda+s)\tau}] .$$

Since the moments of S^* can be obtained from $\Pr\{S^*>t\}$ in the following manner

$$E(S^{*n}) = n\int_0^\infty t^{n-1}\Pr\{S^*>t\}dt ,$$

it follows directly that $E(S^*)$ is merely the value of $\pounds[\Pr\{S^*>t\}]$ at $s = 0$; therefore,

$$E(S^*) = (e^{\lambda\tau}-1)/\lambda .$$

The second moment similarly follows from the derivative of $\pounds[\Pr\{S^*>t\}]$ with respect to s as evaluated at $s = 0$; and the variance clearly follows therefrom as

$$\mathrm{Var}(S^*) = (e^{2\lambda\tau}-2\lambda\tau e^{\lambda\tau}-1)/\lambda^2 ,$$

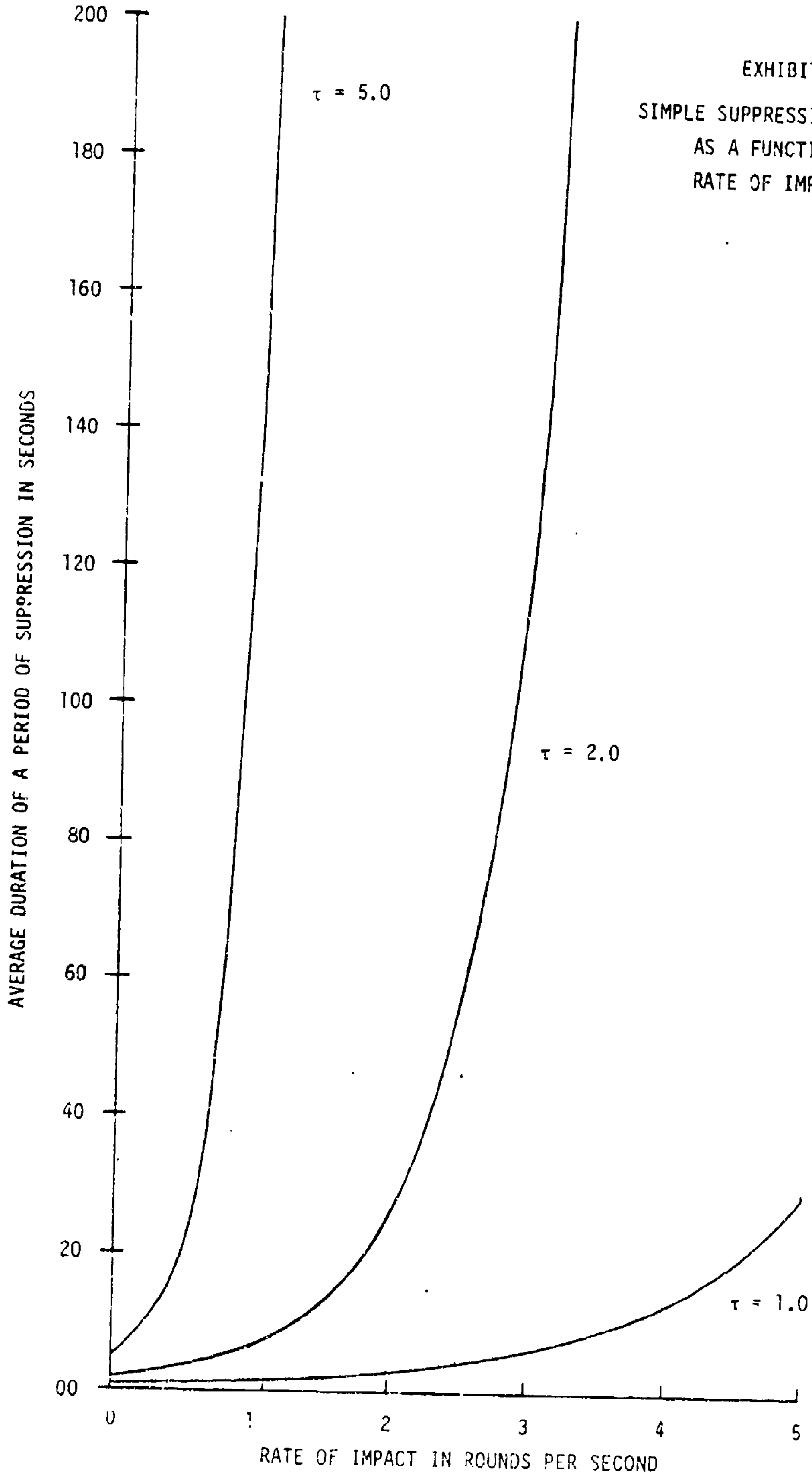
after the appropriate algebra is performed.

The exponential dependency of $E(S^*)$ on λ and τ implies that small increases in the impact rate in the course of an engagement can induce large, sudden increases in the average duration of suppression periods, once a moderate impact rate has been achieved. The similar growth in the variance suggests very substantial fluctuations in those durations. In fact the coefficient of variation for S^* is asymptotically one.

Just how rapidly $E(S^*)$ can change is shown by Exhibit I, following this page. For selected durations τ of the single-round period of suppressive effect, $E(S^*)$ is graphed as a function of the impact rate λ in the region of suppressive affect. When τ is as small as two seconds, slight changes in the impact rate can produce great changes in $E(S^*)$, the average duration of a period of suppression. As Exhibit II shows, those great changes in the average duration of suppression in response to slight variations in the impact rate are matched by the correspondingly great changes caused by slight variations in the duration of a single-round period of suppressive effect. Consequently small discrepancies between assumed durations of suppressive effect and actual durations can introduce great variations in any durations of suppression periods extrapolated therefrom.

EXHIBIT I

SIMPLE SUPPRESSION FORMULA
AS A FUNCTION OF
RATE OF IMPACT λ



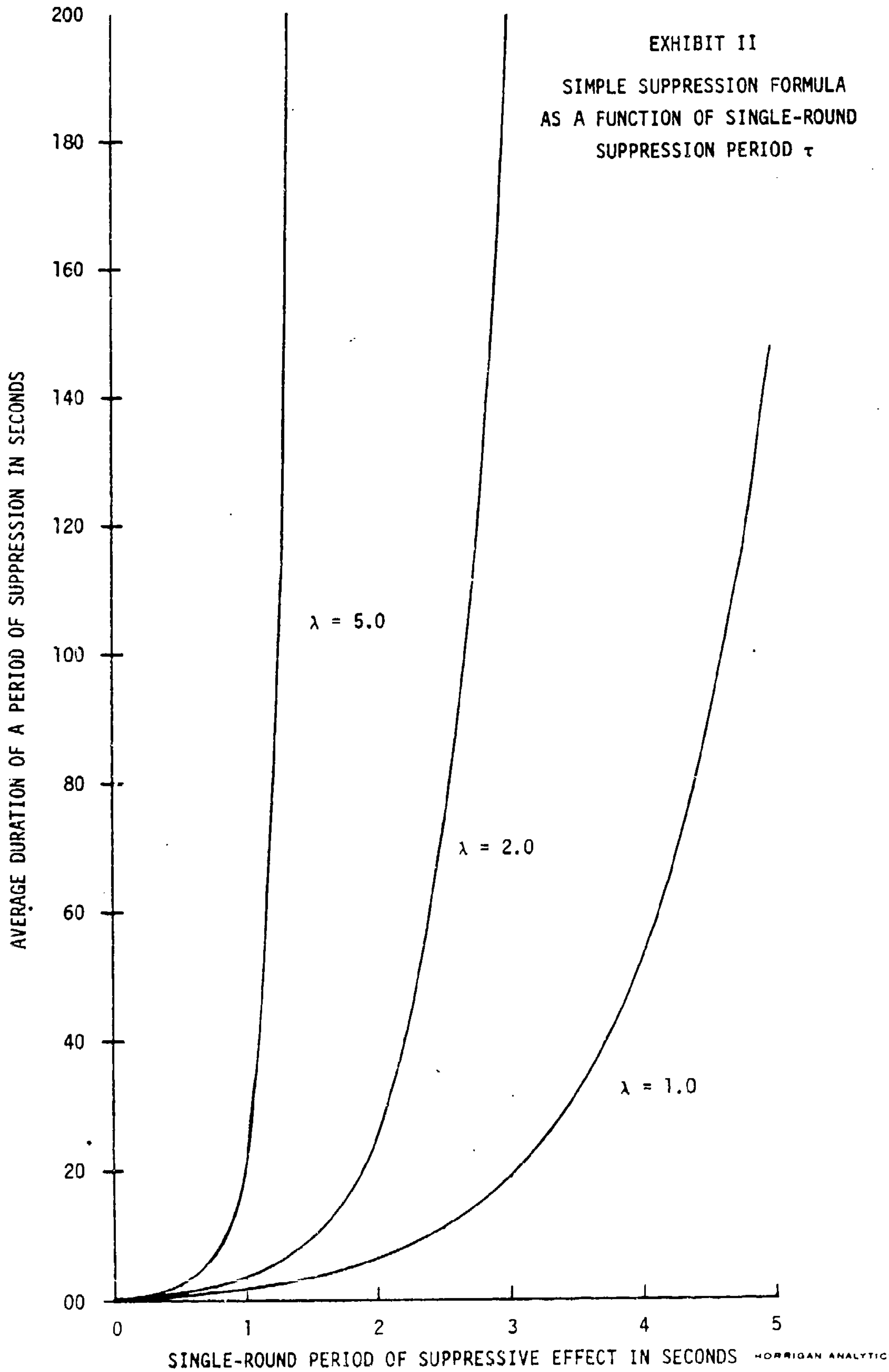


EXHIBIT II
SIMPLE SUPPRESSION FORMULA
AS A FUNCTION OF SINGLE-ROUND
SUPPRESSION PERIOD τ
AVERAGE DURATION OF A PERIOD OF SUPPRESSION IN SECONDS
200
180
160
140
120
100
80
60
40
20
00
λ = 5.0
λ = 2.0
λ = 1.0
0
1
2
3
4
5
SINGLE-ROUND PERIOD OF SUPPRESSIVE EFFECT IN SECONDS
HORRIGAN ANALYTICS

Although these formulas appear new in the context of suppression, they are well-known in other applications; in fact they have a surprising propensity for being rediscovered in new contexts[3]. They may also be derived by more general means than those herein employed, notably by the methods of renewal theory. The derivation just outlined is, however, direct and is the one that led to the formulas in the context of suppression.

DETECTION IMPEDED BY SIMPLE SUPPRESSION

Many search activities in the combat environment are characterized by an exponentially distributed detection time. Any such activity consequently possesses the Markov property for the exponential distribution[4] and is therefore easily adjusted to account for being suspended during periods of suppression. Indeed, a detection may occur only between periods of suppression because the hiatuses they create block all such events while they last; in other respects the search and bombardment activities are presumed independent. The Markov property then insures that the random detection time retains the *same* exponential distribution regardless of the number and duration of preceding periods of suppression and fruitless search. Since $N^*(t)$ is Poisson, it similarly insures that the duration between the end of one period of suppression and the start of the next defines a family of independent, identically distributed random variables.

Accordingly a basic suppression-search cycle exists. It begins with the onset of a period of suppression and ends either with the onset of another period of suppression or a detection, whichever first follows the initial period of suppression. All cycles are identically and independently distributed in duration. The first part of a cycle of course has the duration S^* , that of a simple period of suppression. The last part is the period between the cessation of suppression and either a detection or an impact, whichever occurs first. Since the search activity and the bombardment activity are independent aside from periods of suppression, the probability distribution for the duration from the end of the period of suppression to the end of the cycle follows directly.

Designate that duration by T^* . Since T^* is the minimum of the time to the first detection and the time to the next impact, which are independent, exponentially distributed random variables, it follows that

$$\Pr\{T^*>t\} = e^{-(\lambda+\gamma)t}, \quad t\geq 0$$

when γ is the detection rate in the absence of suppression. A cycle thus has the duration $S^* + T^*$; and the probability that it ends with a detection, an event which is independent of both S^* and T^* , is easily shown to be $\gamma/(\gamma+\lambda)$.

A combatant that is initially suppressed at the time zero may or may not end its first cycle with a detection. The random number of cycles up to and including that on which its first detection occurs has a geometric

distribution. Designate that random number by N^* ; it then has the geometric probability density

$$\Pr\{N^* = n\} = \frac{\gamma}{\gamma+\lambda}\left[\frac{\gamma}{\gamma+\lambda}\right]^{n-1} .$$

Further, designate the random duration of the i-th cycle by C_i^* . Then the time D^* to the first detection is simply

$$D^* = \sum_{1}^{N^*}{}_n \, C_n^*$$

a sum of independent, identically distributed random variables. The average time $E(D^*)$ to the first detection following the onset of a period of suppression is

$$E(D^*) = (1/\lambda+1/\gamma)e^{\lambda\tau} - 1/\lambda ,$$

which is an immediate consequence of the preceding expression for D^* .

Suppression, when taken as a hiatus, is thus seen to have a great effect on detection times. They grow at a rate even greater than the simple suppression periods previously examined. Exhibit III, following this page, illustrates that rapid growth when the average detection time in the absence of suppression is 20 seconds. The average detection time in the presence of suppression is displayed as a function of the impact rate for a single-round period of suppressive effect of unit duration in comparison with the average duration of a single period of suppression under the same circumstances. The strong effect that all-or-nothing periods of suppressive effect have on detection times is manifest.

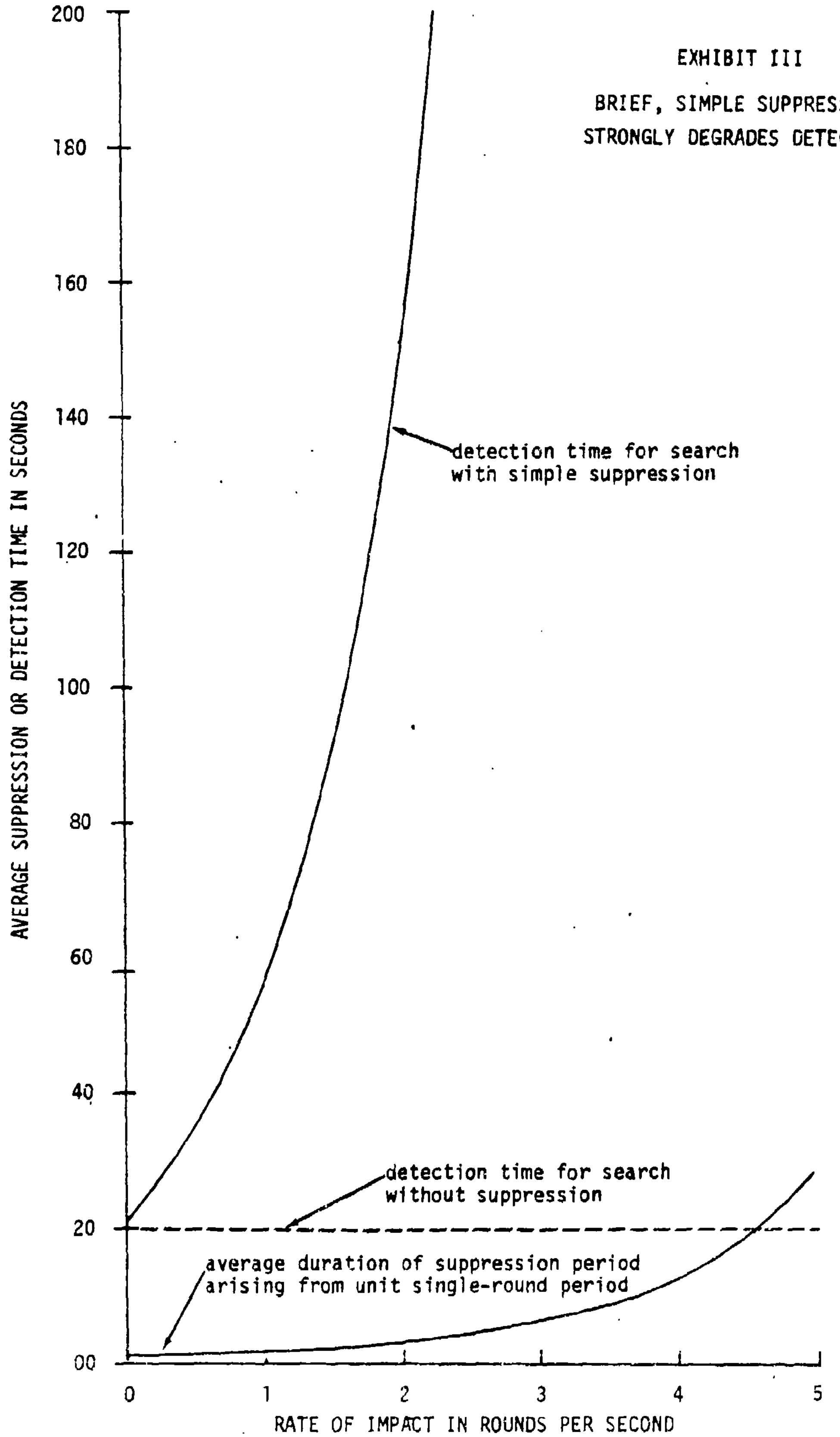
Because the random duration of a suppression-search cycle is $S^* + T^*$, a sum of two independent random variables, the Laplace transformation $C(\cdot)$ of its frequency function is the product of those for S^* and T^* . Since that for S^* follows directly from that of its tail, which is already established, and that for T^* is immediate, their respective product

$$C(s) = \frac{\lambda+s}{\lambda+se^{(\lambda+s)\tau}} \cdot \frac{\lambda+\gamma}{\lambda+\gamma+s} ,$$

with s as the transform variable, gives the Laplace transform of the frequency function for the duration of a suppression-search cycle. As

EXHIBIT III

BRIEF, SIMPLE SUPPRESSION STRONGLY DEGRADES DETECTION



D^* is the sum of N^* such variables, which are identically distributed and are independent both of each other and of N^* , the Laplace transformation of the tail of D^* is

$$\mathcal{L}\Pr\{D^*>t\} = \frac{\lambda+\gamma}{s}[1-C(s)]/[\lambda+\gamma-\lambda C(s)]$$

in which s remains the transform variable. The expected value of D^* , already derived, as well as the higher moments can of course be easily and directly obtained from this equation. Later a more significant use will emerge.

MISS-DISTANCES, WEAPON MIXES, AND GENERALIZED SUPPRESSION

No doubt the most apparent unsatisfactory assumption underlying these formulas is the idealized constant duration of the single-round period of suppressive effect. Further, that duration is required to be independent of miss-distance, and it must be the same for each type of round. Ignoring casualties is of course a shortcoming, but the suppression process itself is not thereby grossly restricted, as it is by the aforementioned assumptions.

Several avenues of generalization for the simple model are thus suggested; and they lead to broadly applicable formulas of remarkable simplicity. The generalized suppression model established therefrom permits:

- Random durations for single-round periods of suppressive effect

- Durations for single-round periods of suppressive effect that depend on miss-distance

- Distinct characteristics for the periods of suppressive effect associated with each ordinance or projectile type

- Segregated, nonuniform delivery of any mixture of projectile types

The general model thus encompasses a substantial number of factors that affect suppression. Durations of suppression for each round type are not only permitted to be distinct, but also they may be random variables with different probability distributions, which may be functions of miss-distance.

Random durations for single-round periods of suppressive effect allow differences in judgment of an individual combatant to be reflected as variations in the single-round suppressive effect of even identical rounds impacting at the same distance. Durations of single-round periods of suppressive effect that deterministically depend on miss-distance are thereby randomized regardless and thus illustrate another variation in the suppressive effect of identical rounds. Permitting single-round

periods of suppressive effect to depend on miss-distance also allows local nonuniformities in projectile delivery to be faithfully represented.

In the simple model all impacts in the area of suppressive affect produce a single-round period of suppressive effect of fixed duration τ ; in the general model a projectile of the i-th type fired from the j-th source produces a single-round period of suppressive effect with the random duration T_{ij}^* , all of which are independently distributed. In the simple model there is only one rate for impact in the area of suppressive affect; in the general model there is one such rate λ_{ij} for each projectile type from each source. The respective impact times of projectiles of each type from each source are assumed to follow independent Poisson processes with the respective intensities λ_{ij} .

Presumably the duration of a single-round period of suppressive effect depends on miss-distance. Given a particular combatant and situation, a particular projectile type, and a fixed miss-distance x , there is a random variable $T^*(x)$ which is the duration of the single-round period of suppressive effect that results from an impact a distance x from the combatant. Of course, the duration of such a suppression period may be taken as function of the miss-distance. In either event, because the miss-distance itself is a random variable, the resulting single-round period of suppressive effect has a random duration.

As indicated above the random duration of this suppression period for a projectile of the i-th type from the j-th source is T_{ij}^* in which dependency on miss-distance is implicit. If the function $s_i(t,x)$ is the probability density for a single-round period of duration t arising from the impact of the i-th projectile type a distance x from the combatant, and if $f_{ij}(x)$ is the probability density governing impacts at x by a projectile of the i-th type from the j-th source, then the expected (average) duration of a single-round period of suppressive effect is

$$E(T_{ij}^*) = \int_0^\infty \int_0^\infty t s_i(t,x) f_{ij}(x)\,dx\,dt \, .$$

The remarkable aspect of the generalized model is that these expected values together with the average impact rates λ_{ij} determine the expected duration of a suppression period and expected detection times as well.

As in the simple model, for an entity to be suppressed for a duration t , there must be an unbroken chain of overlapped, single-round suppression periods which together, from the beginning of the first to begin, to the end of the last to cease, constitute a duration t . Unlike the simple model, the durations of the single-round periods of suppressive effect are no longer the same in duration; short ones and long ones are haphazardly mixed, and many gaps between short ones may be filled by a single long one. Despite this great increase in physical complexity and a comparable increase in mathematical difficulty, there is little change in the formula for the expected duration of a suppression period.

For R round types and N fire sources define λ , the combined impact rate of projectiles in the region of suppressive affect, as follows:

$$\lambda = \sum_{1}^{R}{}_{i} \sum_{1}^{N}{}_{j} \lambda_{ij} .$$

As in the simple model, designate the random duration of an overall suppression period by S^* . Then the expected duration of an overall suppression period in the generalized model is

$$E(S^*) = \frac{1}{\lambda}\left\{\exp\left[\sum_{1}^{R}{}_{i} \sum_{1}^{N}{}_{j} \lambda_{ij} E(T^*_{ij})\right] - 1\right\} ,$$

a remarkably simple formula, which involves only the expected durations of single-round periods of suppressive effect.

When each round type is represented by a distinct single-round period of suppressive effect which is a constant independent of miss-distance, the formula simplifies further. In that case there are no random variations in the duration of a single-round period of suppressive effect. For a fixed round type all such periods are of identical duration. For the i-th round type designate the duration of a single-round period of suppressive effect by τ_i . Because the τ_i are functionally independent of miss-distance, they are consequently independent of the source of fire. Hence, the segregation of impact rates by the source of fire is not necessary in this case. Accordingly, if λ_i is defined by

$$\lambda_i = \sum_{1}^{N}{}_{j} \lambda_{ij} ,$$

then it designates the impact rate of the i-th type of projectile in the

region of suppressive affect. The expected duration of an overall period of suppression is accordingly given by

$$E(S^*) = \frac{1}{\lambda}\left\{\exp\left[\sum_{1}^{R}{}_{i}\lambda_i\tau_i\right]-1\right\}$$

in which S^* again designates the random duration of an overall suppression period and λ the combined impact rate.

EXPECTED DETECTION TIMES IN THE GENERALIZED MODEL

Detection in the generalized model is conceptualized just as it is in the simple model. A combatant cycles between suppression and search until it first makes a detection before the onset of the next suppression period. Despite the greatly increased physical complexity encompassed by the general model there is no proportionate increase in the complexity of the formula for expected detection times. With D^* again designating the random time to a detection by an initially suppressed combatant, it can be shown that

$$E(D^*) = (1/\gamma + 1/\lambda)\exp\left[\sum_{1}^{R}{}_{i}\sum_{1}^{N}{}_{j}\lambda_{ij}E(T_{ij}^*)\right] - 1/\lambda$$

when γ remains the parameter in the exponential distribution of detection time in the absence of suppressive fires. Thus a simple, general, and convenient formula is available for connecting the effect of suppressive fires with the ability to return fires.

When the durations of single-round periods of suppressive effect are assumed constant for a given projectile type a somewhat simpler formula governs:

$$E(D^*) = (1/\gamma + 1/\lambda)\exp\left[\sum_{1}^{R}{}_{i}\lambda_i\tau_i\right] - 1/\lambda$$

in which τ_i again represents the single-round suppression duration assigned to the i-th projectile type, and λ_i designates the corresponding impact rate.

DURATIONS OF SUPPRESSION FOR UNDAMAGED COMBATANTS

These formulas neglect causalties. While that is a minor omission relative to the simple model, it is still a flaw. It tends to lengthen expected detection times because it implicitly ignores the fact that an entity must survive in order to detect. The condition that a combatant survives the rounds impacting in its area of suppressive affect during the suppression periods preceding its making a detection reduces the expected number of such impacts.

How the duration of a period of suppression is affected is easily seen in terms of the simple model. With δ designating the single-round damage probability and $\mathcal{U}(t)$ designating the event that the combatant is undamaged during the time t , the formula

$$E[S^{*}|\mathcal{U}(S^{*})] = [(1+\delta\lambda\tau)/(\delta + \overline{1-\delta}e^{-\lambda\tau})-1]/\lambda$$

gives the expected duration of those periods of suppression during which the combatant is undamaged. In situations in which no damage is possible δ is zero, and $E[S^{*}|\mathcal{U}(S^{*})]$ then equals $E(S^{*})$. For positive δ it is always less than $E(S^{*})$; and it strictly decreases with increasing δ until finally, when δ is one, it becomes τ , the smallest possible period of suppression in the simple model.

Whether the quantitative consequences of using $E(S^{*})$ vice $E[S^{*}|\mathcal{U}(S^{*})]$ are major or minor obviously depends strongly on the single-round casualty probability δ . When it is small and the impact rate is small to moderate, the consequences appear to be negligible. However, whenever it is not small or the impact rate is high, the consequences are major. In such cases the consequences are greater for damaged combatants; for instance, if δ is small and λ moderate, then $E[S^{*}|\mathcal{U}(S^{*})]$ can be about ten percent less than $E(S^{*})$, while $E[S^{*}|\tilde{\mathcal{U}}(S^{*})]$ can be twice $E(S^{*})$. On the other hand, when δ is moderate and λ high, the reverse can easily obtain; $E[S^{*}|\mathcal{U}(S^{*})]$ can be about half $E(S^{*})$, while $E[S^{*}|\tilde{\mathcal{U}}(S^{*})]$ exceeds it by no more than ten percent or so. In either case, those periods of suppression during which casualties occur are much longer than those during which there are none. Combatants, in

effect, are pinned down by suppressive fires for much longer times when damage occurs -- a possibly surprising fact considering the assumed total randomness of the fires.

FRACTIONAL SUPPRESSION AND EXPECTED DETECTION TIMES

Neglect of casualties is not the only flaw in the generalized suppression model. A more fundamental one is the idealization of suppression as a hiatus in the activity of the suppressed combatant. Although that handy idealization is commonly used in modeling suppression, it is none the less counterfactual. Suppressive fires slow down activities; they do not necessarily stop them. Idealizing suppression as a hiatus is adequate only insofar as periods of suppression are considered in abstraction -- without any interaction with combat activities.

Search activities are a case in point. Expected detection times in the presence of suppressive fires can very easily become very long, as Exhibit III illustrates. Simply because those times can be so long, the difference between suppression as a stopping of all activity and suppression as a slowing of it is important. If suppression is truly a hiatus in combat activities, then detections cannot be made during periods of suppression, regardless of their durations. If suppression is anything less total, however, detections will then frequently be made during periods of suppression, particularly when their expected durations are long.

Suppression that is less than total is herein termed *fractional suppression*; during periods of fractional suppression combat activities proceed at a fraction of their unsuppressed rates. Search activities of the type previously defined, that proceed with a search rate γ in the absence of suppression, proceed with the reduced, fractional rate $\eta\gamma$ (for an appropriate η in the unit interval) during periods of suppression. Expected detection times therefore can never exceed $1/(\eta\gamma)$ regardless of the duration of periods of suppression. Fractional suppression and casualty production thus both operate to decrease the duration of detection times.

Idealizing a single-round period of suppressive effect not as a hiatus in a search activity but as reduction in some major factor, for example the solid angle available to the combatant for search, captures a vital characteristic of the interaction of search and suppression. A limit on the efficacy of suppressive fires to inhibit detection is imposed; a point of diminishing return is established. Increasing rates of fire no longer produces progressively greater increases in expected detection times. Instead, successive increases reach a maximum and then become progressively smaller; and the expected detection time can never be forced beyond $1/(\eta\gamma)$. A necessary logical boundary is thus incorporated without which the suppression process itself is compromised.

What fractional suppression means is easily visualized in terms of the example. An upright combatant, for example, typically has a field of

view that is much greater than that available from a crouching or a prone position. Nearby impacts which result in that combatant's taking temporarily a crouching or a prone position thereby introduce fractional suppression by reducing the solid angle available for search activity from that available in an upright position to some smaller portion. As a result the search rate is decreased, and the expected detection time is increased. Impacts in the vicinity of a crouching combatant similarly can cause the solid angle available for search activities to be reduced to that portion available from a prone position. Thus conceived, fractional suppression makes the counterfactuality of suppression as a hiatus obvious.

Quantifying fractional suppression is straightforward. The fraction η itself, in terms of the example, is merely the ratio of the steradian of the solid angle available to the search activity in the presence of suppression to that available in the absence of suppression. The search activity can accordingly be represented by two independent processes, one characterized by the search rate $(1-\eta)\gamma$ and the other by the search rate $\eta\gamma$. The first process arises from search in the solid angle that is unavailable during periods of suppression; the second process arises from search in the solid angle that is always available. Suppression always suspends the first process, but it never affects the second.

Consequently, the random detection time D_1^* associated with the first process behaves exactly the same as the random detection time in the presence of simple suppression previously examined. That random detection time D_2^* associated with the second process of course follows the exponential distribution. The random time $D^*(\eta)$ at which the combatant, cycling between fractional suppression and search, makes its next detection is clearly just the minimum of those two random times. The tail of the distribution of $D^*(\eta)$ is thus

$$\Pr\{D^*(\eta)>t\} = \Pr\{D_1^*>t, D_2^*>t\} = \Pr\{D_1^*>t\}e^{-\eta\gamma t} ,$$

in which the right-most member follows from the independence of the underlying search processes. The n-th moment of $D^*(\eta)$ is thus given by

$$E[D^*(\eta)]^n = n\int_0^\infty t^{n-1}\Pr\{D_1^*>t\}e^{-\eta\gamma t}dt ,$$

which is essentially nothing other than the (n-1)-th derivative of the

previously established Laplace transform $\mathcal{L}\Pr\{D^*>t\}$ of the tail of D^*, after $\eta\gamma$ is substituted for the transform variable and $(1-\eta)\gamma$ is substituted for the original search rate. Consequently, if the variable z is defined by

$$z = \frac{(\lambda+\eta\gamma)[\lambda+(1-\eta)\gamma]}{(\lambda+\gamma)[\lambda+\eta\gamma e^{(\lambda+\eta\gamma)\tau}]},$$

then the expected detection time $E[D^*(\eta)]$ in the presence of fractional suppression is

$$E[D^*(\eta)] = \frac{[\lambda+(1-\eta)\gamma](1-z)}{\eta\gamma[(1-\eta)\gamma+\lambda(1-z)]}.$$

Regrettably, the algebraic simplicity of the expected detection time $E(D^*)$ in simple suppression is lost, but a vital recognition of diminishing returns, which is much more than compensatory, is acquired.

How fractional suppression affects expected detection times is shown in Exhibits IV and V, which follow this page. In both those exhibits the suppression fraction η takes the values: 0.0, 0.05, 0.1, 0.25, and 0.5. The first value, of course, corresponds to the usual idealization of suppression as a hiatus; the values from 0.05 to 0.25 are perhaps more representative. In each exhibit the expected detection time in the absence of suppression is 20 seconds.

In Exhibit IV the single-round period of suppressive effect is 5 seconds, and the rates of impact λ are small to moderate, yet variations in the expected detection times are great. When λ is about 0.1 the range is already significant, and it increases substantially with increases in λ. When λ equals 0.5 the slight difference in the suppression fraction η between total suppression ($\eta = 0$) and nearly total suppression ($\eta = 0.05$) results in an almost 40 percent reduction in the expected detection time. The difference in detection times arising from total suppression and the next level of reduced activity ($\eta = 0.1$) exceeds 50 percent. If η is about 0.1 instead of 0, then the expected detection time is overestimated by 120 percent. The percentage differences increase slightly with smaller expected detection times for detection in the absence of suppression and decrease slightly with larger ones.

A single, high impact rate ($\lambda = 1$) is used in Exhibit V, and the expected detection times for the selected suppression fractions are graphed as functions of the single-round period of suppressive affect τ. The effect of the high impact rate is plain. When τ is about 2.5 seconds, the range

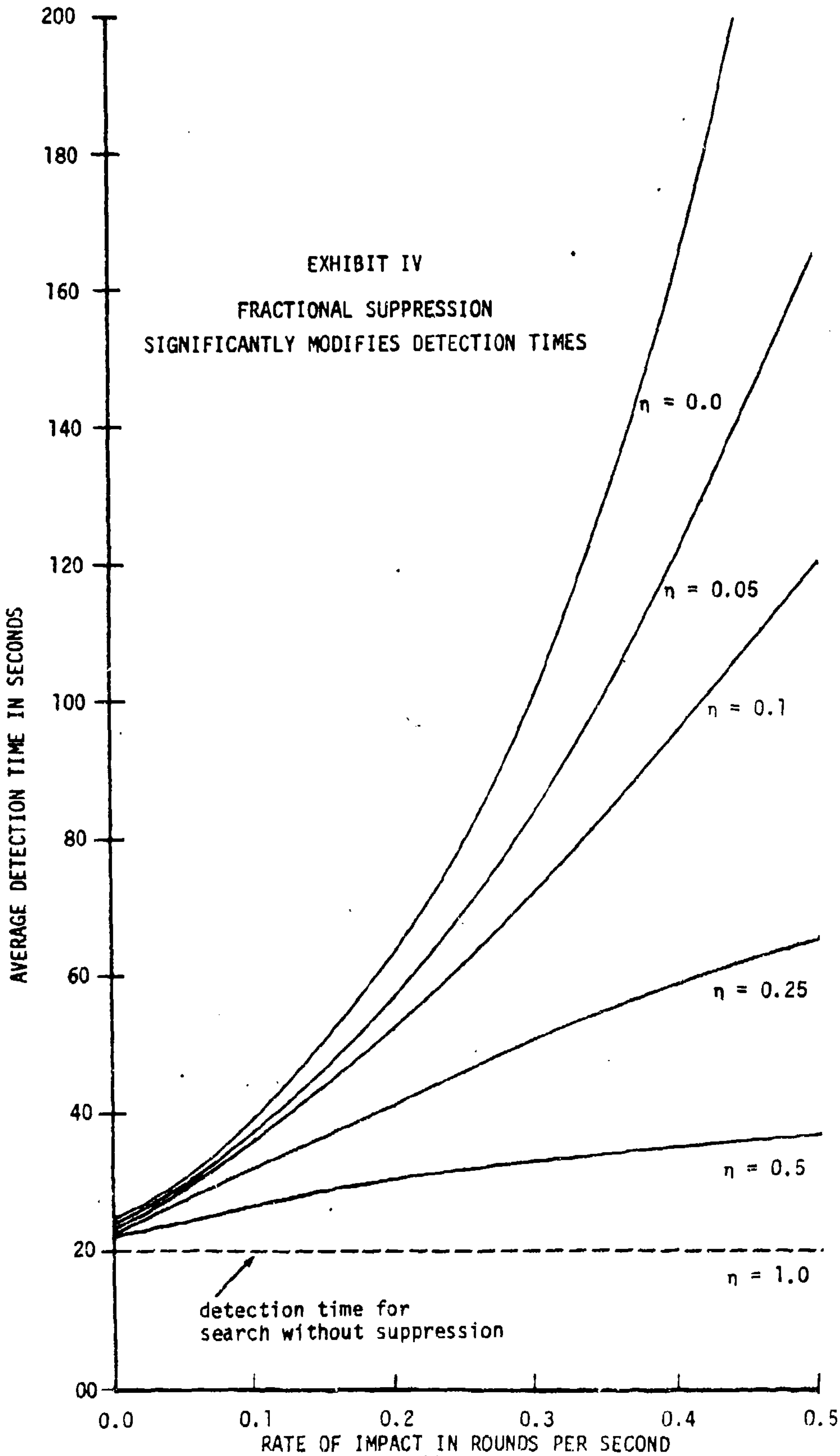


EXHIBIT IV
FRACTIONAL SUPPRESSION
SIGNIFICANTLY MODIFIES DETECTION TIMES
η = 0.0
η = 0.05
η = 0.1
η = 0.25
η = 0.5
η = 1.0
detection time for
search without suppression
AVERAGE DETECTION TIME IN SECONDS
200
180
160
140
120
100
80
60
40
20
00
0.0
0.1
0.2
0.3
0.4
0.5
RATE OF IMPACT IN ROUNDS PER SECOND

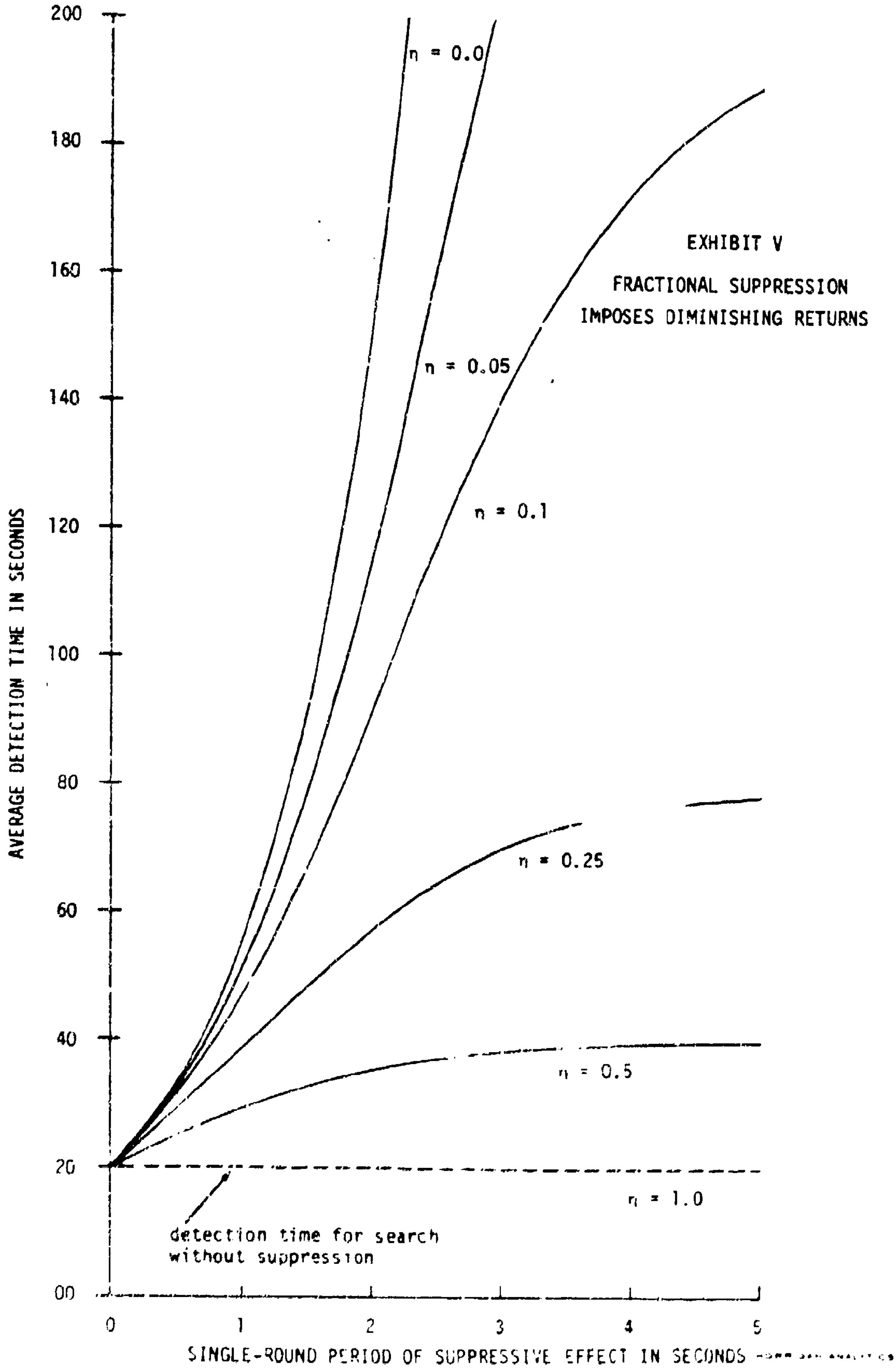


EXHIBIT V

FRACTIONAL SUPPRESSION IMPOSES DIMINISHING RETURNS

of detection time variations matches the maximum encountered in Exhibit IV. For values of τ larger than 2.5 seconds, that range, which is already more than substantial, becomes gross. When τ is about 5 seconds, the expected detection time for all-or-nothing suppression ($\eta = 0$) is nearly ten times greater than that with a suppression fraction η of only 0.05 .

For moderate and higher impact rates and moderate single-round periods of suppressive effect, small variations in the suppression fraction thus produce large to gross changes in the expected detection times. As the exhibits show, particularly Exhibit V, fractional suppression strongly limits the increases in expected detection times that can be obtained by increases in the single-round period of suppressive effect; diminished returns from the longer periods are most apparent. Fractional suppression similarly limits the increases in detection times that can be obtained from increases in the rate of impact, and the diminished returns it imposes are equally impressive. Casualty production further limits such increases in expected detection times. The greatest changes occur relative to departures from all-or-nothing suppression; hence, for all but the lowest impact rates, idealizing suppression as a hiatus is ill-advised.

AD P000608

DIFFERENTIAL MODELS OF COMBAT IN CITIES

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and

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The use of models to study combat has an appeal for everyone endowed with natural curiosity. Broadly speaking, a model is that which is analyzed; it comprises the assumptions of the study. Combat models are usually designed to predict battle outcomes and the optimum mix of weapons, and have been developed and used extensively in recent years.

Analytic combat models are abstract models that have received interest in the operations research community. These models are distinguished by the integration of basic combat events into an overall mathematical structure. Analyses of these models are performed by logically consistent mathematical transformations and deductions. Although analytic combat models may be either stochastic or deterministic, they are almost invariably driven by systems of ordinary differential equations. Thus, there has been little or no use made of the other classical differential theories (such as geometry and partial equations) to describe the structure of a battle. In fact, almost all analytic combat models to date are based on Lanchester

type equations or small modifications thereof, such as the introduction of time (or range) dependent kill rate coefficients. An interesting feature of this type of formulation is the lack of any space variable in the equation system. The inclusion of space variables could allow the natural use of transformations to describe dispersion, concentration and the non-uniform distribution of targets.

Another feature related to this approach is the treatment of mobility. Generally, straight line segments are used to model advance paths with a record kept of the track of each homogeneous unit. This implies that a Lagrangian, rather than an Eulerian, coordinate system is being employed.* A property of Eulerian systems is that they facilitate the treatment of dispersion, bunching and other geometric aspects.

In order to embrace considerations of spatial distribution of forces the notion of combat unit densities is employed. (hereafter referred to as c.u. density), This consideration, while still taking advantage of the procedures of averaging and estimating of the attrition coefficients, affords a more fundamental approach through the explicit use of personnel densities in both space and time.

A derivation of the mathematical model will demonstrate a natural method for handling c.u. densities. The model is

* Eulerian coordinates are field coordinates that apply to locations in time and space and do not denote the locations of individual units. Lagrangian coordinates, which are used in rigid body dynamics, denote the position of an individual unit as it moves about.

developed in Eulerian coordinates with each model component being in general a function of space and time.

The first model component represents the flow of units due to random motion. This is a motion in which the center of the density has no velocity -- a diffusion effect encountered in general area combat. Such a flow is described as

$$f_j^{I}(\bar{x}, t) = -D_j \overline{\nabla n_j}(\bar{x}, t) ,$$

where

D_j = a constant of proportionality $\left(\text{meters}^2/\text{sec}\right)$

n_j = c.u. density of side "n" $\left(\text{c.u.}/\text{meters}^2\right)$

f_j^{I} = flow $\left(\text{c.u.}/\text{sec}\right)$

j denotes a particular homogeneous group of the "n" force .

In this derivation a two dimensional space serves as the battlefield terrain. The derivation is readily extended to a three dimensional space; hence area and linear dimension are completely analagous to the more general notions of volume and area.

The next contribution to the model accounts for a directed flow of c.u. that is non random. This flow is represented as

$$f_j^{II} = n_j \overline{V}_j$$

where $\overline{V}_j = \overline{V}_j(\bar{x}, t)$ is the velocity of flow at the position $\bar{x}$ at time t. The net flow from the random and directed components is taken as

$$\text{(1)} \qquad \bar{f}_j(\bar{x}, t) = -D_j \overline{\nabla n_j}(\bar{x}, t) + n_j(\bar{x}, t)\,\overline{V}_j(\bar{x}, t)$$

The action for a particular area in the absence of attrition

and other sink terms can be expressed as the net rate of unit flow out of this area. This must be

$$(2) \qquad \frac{\partial N_j}{\partial t} = \int \bar{f}_j (\bar{x}, t) \cdot d\bar{l}$$

where N_j is the net number of units and $d\bar{l}$ is an element of the boundry of the area being considered. For a three dimensional problem an element of the boundary surface would correspond to the differential length $d\bar{l}$.

A useful representation for equation (2) can be written with Gauss' theorem,

$$(3) \quad \int \bar{f}_j (\bar{x}, t) \cdot d\bar{l} = \int \bar{\nabla} \cdot \bar{f}_j (\bar{x}, t) \; ds$$

where ds is a patch of the area under consideration. The net outflow can now be expressed as

$$(4) \quad -\frac{\partial N_j (\bar{x}, t)}{\partial t} = \int \bar{\nabla} \cdot \left[-D_j \overline{\nabla n_j} (\bar{x}, t) + n_j (\bar{x}, t) \; \bar{V}_j (\bar{x}, t) \right] ds$$

The expression for the rate of change of the c.u.s in terms of the c.u. densities is simply

$$(5) \qquad -\frac{\partial N_j (\bar{x}, t)}{\partial t} = -\int \frac{\partial n_j}{\partial t} (\bar{x}, t) \; ds$$

Direct substitution of equation (5) into (4) yields

$$(6) \quad \int \left\{ \bar{\nabla} \cdot \left[-D_j \overline{\nabla n_j} (\bar{x}, t) + n_j (\bar{x}, t) \bar{V}_j (\bar{x}, t) \right] + \frac{\partial n_j}{\partial t} \right\} ds = 0 \; .$$

This equation holds over the entire area, therefore it follows that

$$(7) \quad \frac{\partial n_j(x,t)}{\partial t} = \bar{\nabla} \cdot \left[D_j(\bar{x},t)\ \bar{\nabla} n_j(\bar{x},t) \right] - \bar{\nabla} \cdot \left[n_j(\bar{x},t)\ \bar{V}_j(\bar{x},t) \right],$$

which holds in the absence of attrition terms.

The remaining model considerations account for the sink terms associated with attrition. Generally, attrition terms are expressed as

$$(8) \quad S_j(\bar{x},t) = -\sum_i n_i(\bar{x}+\bar{\delta}_i, t)\ A_{ij}(\bar{x},t) \quad .$$

In the case of aimed fire

$$A_{ij}(\bar{x},t) = K_j(\bar{\delta}_i, t)$$

where

$\bar{\delta}_i$ = the range between unit "j" at $\bar{x}$ and attacker "i" at $(\bar{x}+\bar{\delta}_i)$.

$K_j = K_j(\bar{\delta}_i, t)$ = the rate at which a single "j" unit destroys "i" units

For area type fire

$$(9) \quad A_{ij}(\bar{x},t) = K_j'(\bar{\delta}_i, t)\ n_j(\bar{x},t) \quad .$$

Both "K_j" and "K_j'" are referred to as attrition coefficients and are themselves functions of space and time. They are, as one would expect, complex functions of weapon capabilities, target characteristics, allocation procedures for assigning weapons to targets, intelligence, etc.

The attrition terms, when combined with the random motion and the directed flow term, give the general structure of the mathematical model. The total expression is

$$(10)\quad \frac{\partial n_j}{\partial t}(\bar{x}, t) = \bar{\nabla}\cdot\left[D_j(\bar{x}, t)\,\bar{\nabla} n_j(\bar{x},t)\right] - \bar{\nabla}\cdot\left[n_j(\bar{x},t)\,\bar{V}_j(\bar{x},t)\right] - S_j(\bar{x}, t)$$

Whereas the solutions to most analytic models are determined by an initial condition for each equation describing the force (the number of units as the battle begins) the solution to the above partial differential equation requires an initial condition in addition to two boundary conditions (BC) in one dimension and four boundary conditions in the two dimensional model. In consonance with other analytic models that describe heterogeneous forces in combat, outcomes are determined from the solution of sets of partial differential equations. Thus, each heterogeneous force is considered to be composed of homogeneous units each of which is described by its own differential equation.

The system of partial differential equations allows an analyst to specify a highly detailed battle in terms of many combat functions. By the judicious use of proper formulations and the greater number of boundary conditions a flexible model of combat is possible. In particular the boundary conditions can be employed to model some initial placement of personnel at a location on the battlefield, i.e.,

$$n\ (\bar{x}',\ t) = g\ (\bar{x}') \qquad \text{BC}$$

with the function $g\ (x')$ representing this initial force at location x' . If an obstacle or barrier were a significant terrain feature then

$$\frac{\partial n\ (\bar{x},\ t)}{\partial x} = f\ (\bar{x}) \qquad \text{BC}$$

would represent the flow or "leakage" of c.u.s across this obstacle. A perfectly effective minefield could be expressed as

$$f\ (\bar{x}) = 0$$

implying that no "n" forces are able to penetrate this region of space. In short, the boundary conditions for these models give increased

ability to represent tactical situations. Naturally, many other representations for the BCs are possible than the examples cited above.

The net losses in battle are capable of being represented in terms of specific areas for chosen durations. The cost (in c.u. losses) in attacking or defending a specific portion of the battlefield with area σ' in the time interval $\Delta t = (t_2 - t_1)$ is

$$\int_{t_1}^{t_2} \int_{\sigma'} S(\bar{x}, t)\ dsdt$$

Such expressions are useful for formulating and comparing various defensive deployment strategies for ground forces. The trajectory results of the entire action over the complete battlefield are computed by extending the limits of integration,

$$\int_{0}^{\infty} \int_{\sigma} S(\bar{x}, t)\ dsdt$$

The model described here has been used to examine several engagements that are typical of combat in built-up areas. Among these are building assault situations by infantry units and armored attacks from open areas to lines of fortified buildings. The use of variables that describe spatial distribution of forces is particularly appropriate for examining city combat because of the natural canalization of troop movements in urban areas. Specific examples of these engagement models will be discussed at the symposium.

AN OVERVIEW OF THE BATTLE[1] MODEL

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1.0 INTRODUCTION

The purpose of this paper is to present an overview description of the BATTLE model being developed by Vector Research, Incorporated, for the Weapons Systems Evaluation Group (WSEG). The model is intended to describe the joint activities of US Army units and Air Force Tactical Aircraft engaging advancing Soviet forces who are also supported by tactical aircraft. The model is to be used in estimating net assessments and in generating data to make trade-offs among the various forces and systems involved in such an engagement.

Current models such as ATLAS and GACAM which have been used to describe large-scale, joint services, theater-level warfare have been aggregated macroscopic models in that they aggregate individual weapon system effects at the theater level by using a single strength factor (known as the "firepower score") to describe the theater-sized units. Although the existing aggregated "firepower score" models are relatively easy to use, they are known to contain a large number of technical and data problems. In brief, some of the deficiencies are associated with

(a) the use of the "firepower score" force ratio concept as the principal means of driving the attrition process, and
(b) the use of the "firepower score" force ratio concept to determine the rate of FEBA movement.

Two of the most serious problems in the "firepower score" models are

(a) the inability of the models to reflect changes in detailed tactical phenomena (e.g., calls for air support by units engaged at the FEBA), and
(b) the inability of the models to reasonably reflect the significantly different attrition of different weapon systems (which leads to deficiencies in the dynamic modeling of campaigns of any duration, and to problems in producing useful output measures).

The objective of the BATTLE model development is to demonstrate the feasibility of constructing a campaign model which:

(a) does not use the "firepower score" force ratio concept of attrition, but rather models attrition in a way that reflects the internal dynamics of the combat activity and relates to specific weapon system parameters and tactics considered important in small unit engagements,

[1] BAttalion Through Theater Level Engagement

(b) disaggregates the Army by explicitly considering five weapon system types that can individually be attrited in maneuver battalions, as well as artillery, air defense, and helicopter systems, and

(c) drives the FEBA movement activity by other than the "firepower score" force ratio concept.

A first version of the BATTLE model was delivered to the WSEG in May and some initial development tests performed during June and July. Although the BATTLE model will eliminate some of the deficiencies in existing models, it is important to recognize that the model delivered to the WSEG this past summer is a prototype which contains some purposeful simplifications to complete its initial development by that time. It has, however, been structured so that some of the recognized simplified assumptions can be removed and replaced by more realistic ones at a later date. The next section of this overview describes what is contained in the BATTLE model.

2.0 THEATER BATTLEFIELD REPRESENTED

2.1 Geometry: The FEBA in the BATTLE model is divided into parallel segments so that the FEBA is considered piecewise linear over the total theater. Maneuver forces at the FEBA are associated with these segments. Each segment is assumed to be of such a length that it will accommodate a battalion-sized maneuver force (i.e., 2000-8000 meters) and accordingly, the area about each segment is referred to as a "battalion area." The total theater battlefield is divided into sectors to provide for better representation of the spatial allocation of forces. The sectors are parallel areas that run from the FEBA all the way back to the rear area. The model contains ten of these sectors; and accordingly, they may be thought of as areas that might accommodate from Corps to Field Army sized forces.[1] Reserves for maneuver forces at the FEBA (referred to as maneuver forces in reserve) are associated with each of the sectors, as are all rear area forces (artillery, air defense artillery, tactical aircraft, etc.).

2.2 BATTLE Time: Model time is discrete (integer valued) measuring model time periods. These may, but need not, correspond to days (e.g., they may be considered six-hour time periods). Model data must be consistent with the period definition used.

2.3 Forces Represented: The BATTLE model considers maneuver forces at the FEBA (one Blue battalion task force in each battalion area and appropriate Red units allocated to face it), maneuver forces in reserve, artillery forces, attack helicopters, air defense artillery, tactical fixed-wing air forces, and service support forces. Maneuver forces (both at

[1]The initial development tests were conducted with a one-sector version, i.e., the theater was treated as one large sector.

the FEBA and in reserve) can contain armor (tank) systems, antitank systems, infantry with rifles or infantry in armored personnel carriers, infantry with automatic weapons, infantry with area fire weapons, and personnel associated with the different weapon systems. Artillery forces can contain one weapon system class and personnel associated with that system; attack helicopters can contain one weapon system class and personnel associated with it. Air defense artillery forces can contain short-range air defense systems, long-range air defense systems, and personnel associated with these. The tactical air forces are comprised of a number of user selected (input) types of fixed wing aircraft and personnel associated with them. Service support forces are made up of personnel. The model continually keeps track of the number of weapon systems by type and personnel in each of the Red and Blue maneuver forces at the FEBA and the maneuver forces in reserve in each sector. Additionally, the numbers of weapon systems are separately retained for artillery forces, attack helicopter forces, air defense artillery forces, tactical air forces, and service support forces for each of the sectors.

2.4 Supplies Represented: Supplies of the following kinds are separately represented in the model: ammunition for each army weapon system type, ordnance (in user specified categories) for aircraft, aviation gasoline and associated POL (for fixed wing aircraft and attack helicopters), POL for ground systems, and other supplies. Ammunition is assigned to (and separately kept track of by type at each place) individual battalion area maneuver forces, individual artillery forces, individual attack helicopter forces, individual air defense artillery forces, individual tactical air forces, sector stores,[1] and theater stores.[1] POL is assigned to individual battalion-area maneuver forces, sector air forces, sector stores,[1] and theater stores.[1] Finally, the "other" supply category is assigned to sector stores and theater stores.

2.5 Plans and Intentions: For each time period in BATTLE, each maneuver force at the FEBA has a plan which currently may take one of the following values: move forward; hold; hold, delay if moved on; and hold, withdraw if moved on. The list of plans can be expanded to include additional instructions such as: "If successful when moving forward, do not move more than 10 kilometers." Each side has an intention in each sector which currently may be to attack or defend.

2.6 Activities Represented: The model separately represents activities for each of the forces. Maneuver forces at the FEBA can be engaged in either a Blue assault (Red hasty defense), a Blue advance (Red delay), a Blue pursuit (Red withdrawal), relative inaction, Red assault (Blue hasty defense), Red advance (Blue delay), and a Red pursuit (Blue withdrawal). Artillery forces can simultaneously be engaged in (by percent allocation) counter-battery fire, direct support of engaged forces (preparatory fire, counter-preparatory fire, calls for additional fire to battalion area units, and final protective fire), and other fires for attrition[2] on other targets

[1]These are intended to simulate physically removed supplies which the tactical decision rules may not make immediately available.

[2]Artillery systems do not fire smoke or other non-explosive projectiles.

such as reserves, etc. Attack helicopters engage in support of engaged forces (either in delay, withdrawal, or assaults), and air defense artillery engage in air defense fires. The tactical air forces can simultaneously engage in the following activities: air base attack; combat air support (against FEBA maneuver forces, reserve maneuver forces, artillery, and air defense artillery); suppression of air defense artillery; interdiction against convoys, depots, etc.; escort of the above missions; and air defense. The service support forces perform the transfer of supplies (and also serve as targets).

In this section we have discussed what is represented in the model in terms of time, forces (type, composition, and location), supply types and levels, plans and intentions, and activities. Each of these are variables in the model which may change from time period to time period. At the end of each BATTLE time period we can look at values of these variables and think of them as representing a complete description of the battle at that point in time; i.e., a snapshot of the battle at that time. Thus, the values of these variables describe the "state" of the model battle at some point in time and are thus referred to as "state" variables. The processes which cause changes in these state variables are discussed in the following section of this overview.

3.0 PROCESSES FOR DYNAMIC CHANGES IN STATE VARIABLES

A number of processes are modeled in BATTLE which cause dynamic changes in values of the state variables. These are firepower processes; FEBA movement processes; supply consumption processes; weapon system, personnel, and supply replacement processes; reserve utilization processes; and tactical decision processes. A number of processes can occur within an activity. Descriptions of these processes are essentially a description of how an activity is performed. This section describes which processes are contained in the model (with principal emphasis on the firepower processes) and lists their outputs.

3.1 <u>Firepower Delivery Processes</u>: The firepower processes describe different mechanisms of delivering firepower and their effects which cause changes in force composition values and supply levels. These processes may be grouped into four categories: air-to-air, ground-to-air, air-to-ground, and ground-to-ground. Descriptions of the processes in each of these categories are contained in BATTLE as submodels based on specific assumptions about the process being described. Inputs to each of these models are either directly measurable quantities or can be estimated from systems engineering models or more detailed combat process models.

The air-to-air firepower processes separately describe the interactions of the escort versus the interceptor duel and the interceptor versus the attack aircraft duel. Outputs of these submodels consist of the escorts continuing their mission, escorts killed, escorts who return without engaging interceptors, interceptors killed by escorts, interceptors killed by attackers, attackers killed by interceptors, attackers aborting missions, and attackers who continue on to perform their mission. These results are produced both by mission and aircraft type.

The ground-to-air firepower processes describe the interactions of air defense artillery against aircraft on missions to attack ground

targets other than air defense sites,[1] air defense artillery versus aircraft on missions to suppress long-range air defense artillery, and the duel between attack helicopters and ground maneuver forces. The first two firepower processes consider the effects on the aircraft during the flight to its target, while in its target's area, and the return flight; and generate the fraction of aircraft surviving to perform their mission, the fraction of aircraft that perform their mission which survive the return flight, and the fraction of long-range air defense sites suppressed. The model for the maneuver force-attack helicopter duels generates estimates of the number of maneuver force weapons attritted, by type, and attack helicopter attrition while supporting its ground forces.

The air-to-ground firepower processes separately describe the effect of attack aircraft against maneuver units at the FEBA and attack aircraft against other targets such as reserves, supplies, aircraft at air bases, etc. The model describing the firepower process against maneuver forces at the FEBA generates estimates of surviving numbers of weapon systems (by type) in the maneuver force while the model describing firepower effects against other ground targets generates estimates for the remaining number of elements in the target.

The ground-to-ground firepower processes include artillery against maneuver forces at the FEBA, artillery against other targets (other artillery, etc.), maneuver force delays and withdrawals, and maneuver force assault activities. The model describing artillery effects against maneuver forces at the FEBA generates estimates for the expected fraction of surviving forces in a battalion-sized maneuver force (by weapon system type and personnel in that unit), and the model describing artillery effects against other targets generates estimates of the expected fraction of the target and associated personnel surviving. Results of ground-to-ground firepower processes in delay and withdrawal activities are determined outside the model and used as look-up tables for each activity in the model.

The firepower (and other) processes in the assault activity between maneuver forces at the FEBA are computed internally, using VRI's differential models of combat. These models attempt to describe the dynamics of small unit firefights at the FEBA. The models explicitly consider different weapon system types on each side (tanks, anti-tank systems, mounted infantry, etc.), characteristics of these weapon systems (their firing rates, accuracy of fire, projectile flight times, lethality of the projectile), vulnerability of the target by type, firing doctrine of the weapon system (single rounds, burst fire, volley), probabilistic acquisition of targets in the firefight, allocation priorities of weapon systems to targets, maneuver capability of the weapon systems, and the effects of terrain line of sight on acquisition and fire capabilities. Four types of assault scenarios (two for Blue and two for Red) are possible in the BATTLE model, one representing tank heavy assault with mounted infantry and the other a dismounted, infantry heavy, battalion task force. The model computes attrition

[1]By aircraft type and mission.

of weapon systems by type and personnel for the opposing units at different range steps as the assaulting unit closes to the objective. Based on tactical decision rules, the assaulting force may break off the assault or may stop and call for fixed wing air, artillery, or attack helicopter fire support. Output of this model is a complete description of the surviving weapons systems by type and personnel at the end of the assault activity.

3.2 FEBA Movement Process: The FEBA movement process is considered in two parts: the decision for a maneuver force at the FEBA to move and the movement rate, given a decision to move has been made. A decision to move is based on a tactical decision rule which can be dependent upon many state variables. Given the decision to move, movement is computed by looking up an appropriate movement rate from the twelve movement rates accepted as input to the model. These movement rates are different, depending upon the activity being performed (advance, pursuit, successful assault, etc.) for each of the maneuver forces at the FEBA.

3.3 Supply Consumption Process: Consumption of supplies occurs as a result of combat activity and as a result of the passage of time. Consumption during combat is computed separately for the assault activity and other combat activities. Consumption during the assault activity of a maneuver force at the FEBA is computed at each range step in the differential models of combat based on the expected number of rounds fired to achieve the expected attrition calculated in that model. In other combat activities, expenditure of supplies is computed on the same basis as its associated firepower process model. For example, if the firepower model gives effects on a per sortie basis, parallel data items give ammunition and POL expenditure per sortie. Consumption of supplies based simply on the passage of time is intended to simulate combat activities that are not included in the model. This type of consumption for units is in direct proportion to its personnel and weapons system strengths.

3.4 Replacement of Weapon Systems, Personnel, and Supplies: Available weapons systems, personnel, and supplies are bookkept with weapons systems and personnel in the sector reserve forces and they are used as replacements for battalion maneuver forces at the FEBA. This is accomplished by tactical decision rules in any of five ways. In each method, the rules first determine directly the available replacement weapons for each type of battalion for the period. Then, the rules may call for (1) direct replacements to individual battalion areas, (2) averaging the number of weapons and personnel among all "battalions" of the same type in the same sector, (3) assignment of the replacement in proportion to the difference of the present level in a "battalion" from its TO&E level, (4) assignment of the replacement in proportion to another rule determined measure of the "battalions" required replacements (e.g., 90% of TO&E level), and (5) assignment of replacements which approximate the results of assigning replacements to "battalions" so that no "battalion" loses weapons and all "battalions" are brought as close to a constant number of weapons (of the type concerned) as possible. Replacement of weapon systems, personnel, and supplies to the sector stores from the theater stores are modeled by similar tactical decision rules.

3.5 Reserve Utilization Process: Tactical rules determine the retirement of maneuver forces at the FEBA into the reserve and the commitment of reserves or new units to the FEBA. When as a result of retirement or commitment of a maneuver force at the FEBA, the model finds a maneuver force at the FEBA temporarily without an opponent, the Red forces are redistributed into one more or one fewer of its allocated units. A force is distributed only into forces of the same type (there are up to ten types of Red and Blue units in a sector). In creating a new composite force, every force of the same type in the same sector loses a constant fraction of its weapons and personnel in such a way that the new "battalion has the mean strength of all forces in the sector. In redistributing an excess Red "battalion" equal fractions of it are distributed to each other Red force of the same type in the same sector.

3.6 Tactical Decision Processes: The model contains a number of tactical decision rules which attempt to describe the behavioral tactical decision processes which are an integral part of any military activity. Recognizing that little is known regarding how military commanders actually make tactical decisions, the model provides the user with a lot of flexibility to specify realistic tactical decision rules for use in the model. A tactical decision rule is a rule that associates a decision (a choice among alternative courses of action) with joint comparisons between ratios of linear sums of the state variables to comparison thresholds. The user has complete flexibility to specify which state variables are to be considered in the rule, the importance or weighting of each of the variables, and the comparison thresholds' values. Essentially, the user can set the value of any state variable as a function of the values of any other state variables contained in the model. Tactical decision rules in BATTLE are used to allocate forces and supplies to sectors; determine which maneuver forces at the FEBA will retire to the reserves; determine how many maneuver forces in reserve will go to the FEBA; govern the assignment of weapons and personnel to maneuver forces at the FEBA as replacements; assign theater intentions and plans for maneuver forces at the FEBA; determine activities of maneuver forces at the FEBA; determine fixed wing tactical air, artillery, and attack helicopter assignments to missions; determine whether forces engaged in an assault (fixed defense) will call for support and when they will break off; and control the FEBA shape.

4.0 MODEL INPUT, OUTPUT, REVIEW PROCEDURE, AND STATUS

4.1 Model Input and Output: Categories of inputs to the BATTLE model are weapon performance data, tactical rule data, and initial force inventory and deployment data. Outputs provided in the current version of the model include:

(1) Daily and cumulative weapon system losses by weapon type.

(2) Daily and cumulative casualties.

(3) Supply totals by type of supply.

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A METHOD FOR DETERMINING INDIVIDUAL AND COMBINED WEAPONS EFFECTIVENESS MEASURES UTILIZING THE RESULTS OF A HIGH-RESOLUTION COMBAT SIMULATION MODEL

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INTRODUCTION

The Gaming and Simulations Department of General Research Corporation/Operations Analysis Division has recently completed a study entitled "NATO Combat Capabilities Analysis II" (COMCAP II) under the sponsorship of ODCSOPS. One of the principal objectives of the study was to develop weapon effectiveness values (WEVs) and unit effectiveness values (UEVs) for representative U.S. and Soviet forces engaged in mid-intensity combat in Western Europe, circa 1976. The objectives of the study were attained by analyzing killer/casualty data generated by an exercise of the Division Battle Model (DBM) over some six days of simulated warfare in the European theater. This paper presents a mathematical description and justification of the methodology, which was employed in the study, for determining the effectiveness values. The paper appears as Appendix D of the COMCAP II final report.

DISCUSSION

Consider two opposing forces, Blue and Red, engaged in military combat. Suppose Blue has b distinct types of weapons and Red has r distinct types of weapons.

Let:

$n_{Bi}(t)$ = the number of Blue type i weapons remaining at time t after start of the battle ($i=1,2,\cdots,b$).

$n_{Rj}(t)$ = the corresponding number of Red type j weapons ($j=1,2,\cdots,r$).

V_{Bi} = the (time-independent) "value" of a Blue type i weapon.

V_{Rj} = the (time independent) "value" of a Red type j weapon.

The goal of COMCAP II is to assign numerical values to the parameters (the WEVs), V_{Bi} and V_{Rj}, such that: (1) the magnitudes of the values indicate the relative worth (in terms of combat effectiveness) of individual weapons; and (2) the resulting values of the linear combinations (the UEVs), $\sum_{i=1}^{b} V_{Bi}\, n_{Bi}(0)$ and $\sum_{j=1}^{r} V_{Rj}\, n_{Rj}(0)$, are "good" measures of the relative strengths of the opposing forces.

(4) Total weapon system survivors by weapon type.

(5) Total personnel survivors in maneuver units.

(6) Total rear area personnel survivors.

(7) Numbers of task forces, weapons, and personnel in reserves.

(8) Numbers of sorties flown on each mission by each aircraft type.

(9) For each battalion area maneuver unit (daily):

Number of weapon systems (by type), personnel, and supplies
FEBA position
Activity

(10) Casualties (by location) and weapon system (by type) losses by system type which inflicts the attrition

4.2 Human Review Procedure: Recognizing that the tactical decision rules may at times result in some anomalies during the course of a 180-day war, or that the user may wish to change a particular decision during the course of a large-scale battle, a human review procedure allows the user a capability to replay a campaign with modifications. The user can direct that any state variable be set to a new value at a prespecified time during a war. This might, for example, be used to change an originally specified allocation variable or an inappropriate theater intention.

4.3 Model Status: The prototype version of the BATTLE model has been developed, programmed in ANSI FORTRAN, debugged, and is operating on both VRI's computer (360/67) and WSEG's CDC 6400. A data base has been formulated for the development testing which involves analysis of parametric variations in force inventory, tactical rules, and weapon performance data. The purpose of the development tests is to determine if (a) one can trace the cause-effect relationship between input variations and output results, and (b) given the input, the output results are consistent with military intuition and/or serve as a basis for changing that intuition. Some results of these development tests will be presented at the symposium.

The methodology adopted for attaining this twofold goal is derived from the following intuitively appealing

Major Premise:

> The total value of a number of weapons of a given type is directly proportional to the total value of the opposing force destroyed by those weapons per unit time.

In what follows it is first shown that the methodology arising from this premise has some interesting implications in connection with classical Lanchester theory; a justification of certain basic model assumptions is also presented; next, an iterative method for solving the resulting equations is described; and, finally, the procedure is illustrated via a numerical example.

Matrix notation is used throughout the discussion. In addition to those given above the following definitions are employed:

B = Blue's (bxr) "kill rate matrix" = $\left[\alpha_{Bij}\right]$

α_{Bij} = the constant rate at which a single Blue type i weapon kills Red type j weapons.

R = Red's (rxb) "kill rate matrix" = $\left[\alpha_{Rji}\right]$

α_{Rji} = the constant rate at which a single Red type j weapon kills Blue type i weapons.

$\overline{V}_B$ = the column vector $\left[V_{Bi}\right]$ with b components.

$\overline{V}_R$ = the column vector $\left[V_{Rj}\right]$ with r components.

$\overline{n}_B(t)$ = the column vector $\left[n_{Bi}(t)\right]$ with b components.

$\overline{n}_R(t)$ = the column vector $\left[n_{Rj}(t)\right]$ with r components.

The elements of the matrices, B and R, are measures of the killing power of individual firers against different types of targets. In COMCAP II, estimates of these measures are obtained by grouping DBM killer/casualty data into discrete sets of small unit engagements according to Blue posture--delay, defense, and counterattack. Specifically, for each such set of engagements,

$$\alpha_{Bij} = \sum_{m=1}^{E} K_{Bijm} \Big/ \sum_{m=1}^{E} n_{Bim} \, \Delta t_m, \text{ and}$$

$$\alpha_{Rji} = \sum_{m=1}^{E} K_{Rjim} \Big/ \sum_{m=1}^{E} n_{Rjm} \, \Delta t_m,$$

requiring the additional definitions:

E = the total number of small unit engagements in the set.

K_{Bijm} = the total number of kills by Blue type i weapons of Red type j weapons in the mth engagement.

n_{Bim} = the initial number of Blue type i weapons in the mth engagement.

Δt_m = the duration of the mth engagement.

K_{Rjim} = the total number of kills by Red type j weapons of Blue type i weapons in the mth engagement.

n_{Rjm} = the initial number of Red type j weapons in the mth engagement.

Also: a "heterogeneous force" is defined as a force comprising weapons with differing characteristics - tanks, TOWs, rifles, etc.; a "homogeneous force" is defined as a force comprising identical weapons; dots are used to denote time derivatives; and superscript T denotes matrix transposition. Other definitions are provided as needed.

<u>Connection Between the Methodology and Lanchester Theory</u>

Using the notation just defined, Lanchester's square law for the attrition of <u>heterogeneous</u> forces engaged in combat may be stated mathematically as

$$\dot{\bar{n}}_R(t) = -B^T \bar{n}_B(t) \tag{1}$$

$$\dot{\bar{n}}_B(t) = -R^T \bar{n}_R(t) \;; \tag{2}$$

i.e., the rate at which targets of a given type are attrited is equal to a weighted sum of the numbers of firers of a given type on the opposing side, the weights being the rates at which the individual firers kill the targets. Denote the total strength of the Blue force at time t by $U_B(t)$, a weighted sum of the number of Blue weapons,

$$U_B(t) = \bar{V}_B^T \bar{n}_B(t) \tag{3}$$

and the corresponding strength of the Red force by $U_R(t)$, a similar sum,

$$U_R(t) = \bar{V}_R^T \bar{n}_R(t) \tag{4}$$

where $\bar{V}_B$ and $\bar{V}_R$ are the yet-to-be-determined vectors of the Blue and Red WEVs. (Note that, if $\bar{V}_B$ and $\bar{V}_R$ are selected "properly," $U_B(0)$ and $U_R(0)$ are the Blue and Red UEVs.) Further, <u>as a direct consequence of the major premise stated earlier</u>, the relationships between the Red and Blue WEVs may be written

$$\beta_B \bar{V}_B = B \bar{V}_R \tag{5}$$

and

$$\beta_R \bar{V}_R = R \bar{V}_B \tag{6}$$

where β_B and β_R are positive constants also to be determined.

Using equations (1), (3), and (4), equation (5) transforms successively to

$$\bar{V}_R^T B^T = \beta_B \bar{V}_B^T$$

$$-\bar{V}_R^T (B^T \bar{n}_B(t)) = -\beta_B (\bar{V}_B^T \bar{n}_B(t))$$

$$\bar{V}_R^T \dot{\bar{n}}_R(t) = -\beta_B U_B(t)$$

and

$$\dot{U}_R(t) = -\beta_B U_B(t). \tag{7}$$

Similarly, using equations (2), (3), and (4), equation (6) transforms to

$$\dot{U}_B(t) = -\beta_R U_R(t). \tag{8}$$

Equations (7) and (8) have the form of Lanchester's square law for the attrition of homogeneous forces, where β_B is the rate at which an "average" Blue weapon kills "average" Red weapons, and β_R is the rate at which an "average" Red weapon kills "average" Blue weapons. Thus, equations (3) - (6) (assuming that equations (5) and (6) can be solved to yield unique values of β_B, β_R, $\bar{V}_B$ and $\bar{V}_R$) imply that one can go from a heterogeneous Lanchester model represented by equations (1) and (2) to an equivalent homogeneous Lanchester model represented by equations (7) and (8). This interesting (and important) fact was first noted by Dare and James[1] and subsequently elaborated upon by Thrall[2] and Anderson.[3*]

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[1] Dare, D.P., and James, B.A.P., "The Derivation of Some Parameters for a Corps/Division Model from a Battle Group Model," Defense Operation Analysis Establishment Memorandum 7120, Ministry of Defense, West Byfleet, United Kingdom, July 1971 (CONFIDENTIAL).

[2] Thrall, Robert M., and Associates, Final Report to US Army Strategy and Tactics Analysis Group (RMT-200-R4-33), May 1972.

[3] Anderson, Lowell B., "A Method for Determining Linear Weighting Values for Individual Weapons Systems," Institute for Defense Analyses, Improved Methodologies for General Purpose Forces Planning (New Methods Study) Working Paper WP-4, December 1971.

[*] The author is indebted to Dr. Anderson forbringing to his (the author's) attention the earlier works of Thrall, and Dare and James.

Equations (5) and (6) may be combined to yield

$$(\beta_B \beta_R I_r - R B) \bar{V}_R = \bar{0}_r \tag{9}$$

and

$$(\beta_B \beta_R I_b - B R) \bar{V}_B = \bar{0}_b \tag{10}$$

where I_r and I_b are, respectively, r^2 and b^2 identity matrices; $\bar{0}_r$ and $\bar{0}_b$ are correspondingly-dimensioned null column vectors. As further noted by Dare and James,[1] Spudich,[4] Thrall,[2] and Anderson,[3] these equations, <u>in most cases</u>, determine the product $\beta_B \beta_R$ uniquely and the components of V_B and V_R to within an arbitrary scaling factor for each of the vectors.*

In general, two additional scaling relationships must be specified in order to permit a unique determination of values of β_B, β_R, V_B and V_R. Among the relationships that have been assumed in other studies, where, it must be emphasized, <u>the goals were not necessarily the same as those of COMCAP II</u>, are those of

Spudich[4]: $$\beta_B = \bar{V}_R^T \bar{n}_R(0), \quad \beta_R = \bar{V}_B^T \bar{n}_B(0) \tag{11}$$

Dare and James[1]:

$$\sum_{i=1}^{b} V_{Bi} = \sum_{j=1}^{r} V_{Rj} = 1 \tag{12}$$

and

Thrall[2]:

$$\beta_B = \sum_{j=1}^{r} V_{Rj}, \quad \beta_R = \sum_{i=1}^{b} V_{Bi}. \tag{13}$$

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[4] Spudich, John, "The Relative Kill Productivity Exchange Ratio Technique," Booz-Allen Applied Research, Inc., Combined Arms Research Office, no date given. (A similar discussion is presented in TAB E, Appendix II to Annex L of the TATAWS III Study, Headquarters, US Army Combat Developments Command, Tank, Antitank and Assault Weapons Requirements Study (U), Phase III, December 1968 (SECRET-NOFORN).

*Provided the matrices BR and RB are "irreducible," there is one and only one value of the product $\beta_B \beta_R$ that leads to nonnegative values of the components of V_B and V_R - namely, the maximum eigenvalue of BR and RB (it is the same for both). The matrices are "reducible" (not irreducible) if at least two opposing weapons types are not interacting directly with the other participants in the battle. In the COMCAP II DBM exercise the problem of reducibility did not arise. For a thorough discussion of matrix reducibility and its implications in weapon effectiveness analyses see Thrall.[2]

In COMCAP II the relationships are taken to be

$$a_B = a_R \ (=1/c), \ V_{B1} = 1 \qquad (14)$$

where the M60A3 tank is assigned the role of the Blue type 1 weapon.

There are two principal arguments for employing equations (14), rather than (11), (12), or (13), in COMCAP II. The arguments are presented below.

Recall that, at the outset, it was stated that the first part of the goal of COMCAP II is to assign numerical values to the parameters (the WEVs) V_{Bi} and V_{Rj} such that the magnitudes of the values indicate the relative worth of individual weapons. Equations (14) result in WEVs for both Blue and Red that are all measured relative to the worth of the same weapon - the M60A3 tank. Thus, if by using equations (14) it turns out that $V_{R2} = V_{B2} = V_{B3} = 2$: one can infer that a Red type 2 weapon, a Blue type 2 weapon, and a Blue type 3 weapon are equally effective, and each is worth two M60A3s. On the other hand, if by using equations (11), (12), or (13) it turns out that $V_{R2} = V_{B2} = V_{B3} = 4$: one can only infer that a Blue type 2 weapon and a Blue type 3 weapon are equally effective; nothing can be inferred about their effectiveness as compared to a Red type 2 weapon. The point being made here is this: equations (14) lead to a set of relative values, the relativity extending not only to the weapons within a Blue force or a Red force but across forces as well; equations (11), (12), or (13) also lead to relative values, but the relativity extends only to the weapons within a force, not across forces.

This completes the first argument for employing equations (14) in COMCAP II.

The second argument--a rather lengthy one--is based on a consideration of equations (7) and (8): Lanchester's square law for homogeneous forces. The solutions to these equations for $U_B(t)$ and $U_R(t)$ as functions of time are well known (see Morse and Kimball[5] for example). They are

$$\frac{U_B(t)}{U_B(0)} = \cosh\left(\sqrt{a_B a_R}\, t\right) - \frac{1}{\sqrt{G}} \sinh\left(\sqrt{a_B a_R}\, t\right) \qquad (15)$$

for the Blue force, and

$$\frac{U_R(t)}{U_R(0)} = \cosh\left(\sqrt{a_B a_R}\, t\right) - \sqrt{G} \sinh\left(\sqrt{a_B a_R}\, t\right) \qquad (16)$$

for the Red force, where G is defined as

$$G = \frac{a_B U_B^2(0)}{a_R U_R^2(0)} \,. \qquad (17)$$

[5] Morse, Philip M., and Kimball, George E., "Methods of Operations Research," The M.I.T. Press, Cambridge, Massachusetts, August 19[illegible].

Dividing each side of equation (15) by the corresponding side of (16) and taking derivatives with respect to time it is readily shown that the designation of the "superior" force is determined by the value of G. For example, $G > 1$ implies that

$$\frac{d\left(\frac{U_B(t)}{U_R(t)}\right)}{dt} > 0$$

and Blue is the superior force since the ratio of the strength of the Blue force to the strength of the Red force increases monotonically with time. On the other hand, $G < 1$ implies that

$$\frac{d\left(\frac{U_R(t)}{U_B(t)}\right)}{dt} < 0,$$

and, by the same reasoning, Red is the superior force. (If $G = 1$, $U_B(t) \;/\; U_R(t) = U_B(0) \;/\; U_R(0)$ for all t and neither side has the advantage.)

Now, from equations (3) and (5) it may be deduced that

$$\beta_B\, U_B^{\,2}(0) = (\bar{V}_R^{\,T}\, B^T\, \bar{n}_B(0))\; (\bar{V}_B^{\,T}\, \bar{n}_B(0))$$

and, from equations (4) and (6) that

$$a_R\, U_R^{\,2}(0) = (\bar{V}_B^{\,T}\, R^T\, \bar{n}_R(0))\; (\bar{V}_R^{\,T}\, \bar{n}_R(0)).$$

It follows, then, that

$$G = \left(\frac{\bar{V}_R^{\,T}\, B^T\, \bar{n}_B(0)}{\bar{V}_R^{\,T}\, \bar{n}_R(0)}\right) \Bigg/ \left(\frac{\bar{V}_B^{\,T}\, R^T\, \bar{n}_R(0)}{\bar{V}_B^{\,T}\, \bar{n}_B(0)}\right). \tag{18}$$

The implications of this equation are quite interesting. It is evident from the equation that the value of G is <u>independent</u> of the method by which the vectors $\bar{V}_B$ and $\bar{V}_R$ are scaled. Therefore, the relationships (11) - (14) (or any other scaling relationships for that matter) <u>all lead to the same value of G; they also all lead to the same value of the right-hand side of equation (15), and the same value of the right-hand side of equation (16)</u>.

Again recall that, at the outset, it was stated that the second part of the goal of COMCAP II is to determine the vectors V_B and V_R such that the linear combinations $\bar{V}_B^{\,T}\, \bar{n}_B(0)$ and $\bar{V}_R^{\,T}\, \bar{n}_R(0)$ (i.e., the UEVs $U_B(0)$ and $U_R(0)$) are "good" measures of the relative strengths of the Blue and Red force. If equations (14) are assumed, it follows from equation (17) that

$$\frac{U_B(0)}{U_R(0)} \doteq \sqrt{G}. \tag{19}$$

Under this assumption, then, $U_B(0) > U_R(0)$ implies that Blue is superior; $U_B(0) < U_R(0)$ implies that Red is superior; and $U_B(0) = U_R(0)$ implies that the forces are equal. The assumption of equations (14), therefore, leads to values of $U_B(0)$ and $U_R(0)$ that are, in fact, "good" measures and a meaningful "force ratio," F, may be defined as

$$F = \frac{U_B(0)}{U_R(0)} . \tag{20}$$

Blue is superior, inferior, or equal to Red accordingly as $F > 1$, $F < 1$, or $F = 1$.

Alternatively, if equations (11) are assumed, it follows from equations (5), (6) and (18) that

$$F = \frac{U_B(0)}{U_R(0)} = G . \tag{21}$$

Hence, the assumption of equations (11) also leads to a meaningful force ratio, F. However, by comparing equations (21) and (17) it is evident that the assumption of equations (11) is tantamount to assuming that

$$\beta_B U_B(0) = \beta_R U_R(0),$$

or, equivalently, that the total Red strength destroyed per unit time is equal to the total Blue strength destroyed per unit time - an assumption that lacks credibility.

Finally, if either equations (12) or (13) are assumed, the resulting ratio, F, is not meaningful. The value of F under either of these assumptions gives no indication whatsoever as to which side is the superior force; under either of these assumptions the calculated value of F, for example, can be considerably less than unity while the corresponding value of G is considerably greater than unity.

This completes the second argument.

In light of the preceding arguments, assumptions (14) are clearly superior to the three alternatives considered, insofar as their applicability to the COMCAP II study is concerned. That is not to say, however, that the alternatives would not be useful in other studies where the goals are different from those of COMCAP II.

The justification of assumptions (14) having been established, equations (15) and (16) may be written

$$\frac{U_B(t)}{U_B(0)} = \cosh(t/c) - \frac{1}{F}\sinh(t/c) \qquad (22)$$

and

$$\frac{U_R(t)}{U_R(0)} = \cosh(t/c) - F\sinh(t/c) \qquad (23)$$

where

$$c = 1/\beta_B = 1/\beta_R$$

$$V_{B1} = 1$$

$$F = \frac{U_B(0)}{U_R(0)} = \frac{\overline{V}_B^T\,\overline{n}_B(0)}{\overline{V}_R^T\,\overline{n}_R(0)}$$

and the values of c, $\overline{V}_B$, and $\overline{V}_R$ are obtained by solving equations (5) and (6). Eliminating the explicit use of the parameter, t, from equations (22) and (23) leads to the "state equation" relating Blue's strength to Red's corresponding strength at any instant after the start of battle,

$$\sqrt{\frac{1 - \left[U_R(t)/U_R(0)\right]^2}{1 - \left[U_B(t)/U_B(0)\right]^2}} = F. \qquad (24)$$

For a given value of F, if one specifies a fraction of the initial strength remaining on one side - say a "break threshold" - the corresponding fraction remaining on the opposing side may be determined from this equation.

Equations (22) - (24) should prove useful in calculating the attrition of forces in highly aggregated war games.

In sum, then, through the use of calculated weighting factors (the WEVs), the COMCAP II methodology converts two opposing heterogeneous forces into two opposing homogeneous forces, both comprising identical weapons. The only difference in the opposing homogeneous forces lies in their respective initial numbers of weapons (the UEVs). The force with the larger UEV is the superior force. The conversion to homogeneous forces permits one to use classical Lanchester theory to compute the relative attrition of forces in highly aggregated war games.

Solution of the WEV Equations

We turn next to the solutions of equations (5), (6), and (14)

$$\beta_B\,\overline{V}_B = B\overline{V}_R$$

$$\beta_R\,\overline{V}_R = R\overline{V}_B$$

$$\beta_B = \beta_R = 1/c$$

$$V_{B1} = 1$$

for the components $\overline{V}_B$ and $\overline{V}_R$ (the WEVs) and the constant, c, (the reciprocal of the average kill rate).

These equations may be combined to yield

$$\overline{V}_B = c^2 \, BR \, \overline{V}_B \, , \tag{25}$$

a relationship involving only c and the Blue WEVs. Let $\lambda = c^2$. A rapidly converging algorithm leading to unique values of λ and the components of $\overline{V}_B$ and $\overline{V}_R$ is given by the following sequence of operations, where the superscript (j) denotes values at the end of the jth iteration.

Step 1. Set $j = 1$.

Step 2. Set all the components of $\overline{V}_B^{(j)}$ equal to unity.

Step 3. Calculate successively:

$$\overline{W}^{(j)} = BR \, \overline{V}_B^{(j)} \, ,$$

$$\lambda^{(j)} = \frac{1}{W_1^{(j)}} \quad (W_1 \text{ is the first component of } \overline{W}),$$

$$\overline{V}_B^{(j+1)} = \lambda^{(j)} \, \overline{W}^{(j)}.$$

Step 4. Repeat Step 3, incrementing j by 1 at each iteration, until $\lambda^{(j+1)} = \lambda^{(j)}$ to within a specified degree of accuracy. The process converges to a unique value of λ and the vector $\overline{V}_B$ with $V_{B1} = 1$.*

Step 5. Calculate:

$$c = \sqrt{\lambda}$$

$$\overline{V}_R = cR \, \overline{V}_B.$$

The iterative procedure is a variation of Hildebrand's[6] method for determining the maximum eigenvalue of a matrix. Proof of the convergence of the method is given on Pages (68-87) of the reference.

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*As previously discussed, it is assumed that the matrix BR is irreducible. See Thrall.[2]

[6]Hildebrand, F. B., "Methods of Applied Mathematics," Prentice-Hall, Inc., Englewood Cliffs, New Jersey, June 1963.

Sample Problem

The ultimate worth of any mathematical model is determined by the degree to which it can be used to solve real-world problems. To illustrate how the foregoing discussion might be used in a practical sense the following sample problem is posed and solved.

Consider a single battle involving two distinct types of weapons on either side with $n_{B1}(0) = n_{R1}(0) = 100$, $n_{B2}(0) = n_{R2}(0) = 25$; i.e.,

$$\bar{n}_B(0) = \bar{n}_R(0) = \begin{bmatrix} 100 \\ 25 \end{bmatrix}.$$

From previously accumulated battle data, Blue's kill rate matrix, B, has been estimated to be

$$B = \left[\alpha_{Bij}\right] = \begin{bmatrix} .1 & .05 \\ .05 & .1 \end{bmatrix}$$

and Red's kill rate matrix, R, by

$$R = \left[\alpha_{Rji}\right] = \begin{bmatrix} .05 & .05 \\ .1 & .05 \end{bmatrix}$$

where the rates are measured in kills per weapon per hour. Using the COMCAP II methodology and the related Lanchester equations answer the following questions:

Question 1. What are the relative values (the WEVs) of the individual weapons in the battle, assuming $V_{B1} = 1$?

Question 2. What are the relative strengths of the forces at the beginning of the battle (the UEVs), and the force ratio, F?

Question 3. The break threshold of both sides is set at 30 percent loss of strength. What is the percent loss of strength of the "winner" when the "loser" breaks?

Question 4. How long does the battle last before the loser breaks?

Solution

Question 1

First perform the matrix multiplication:

$$BR = \begin{bmatrix} .1 & .05 \\ .05 & .1 \end{bmatrix} \begin{bmatrix} .05 & .05 \\ .1 & .05 \end{bmatrix} = \begin{bmatrix} .01 & .0075 \\ .0125 & .0075 \end{bmatrix}.$$

Set $\bar{V}_B^{(1)} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$.

Now perform the iterations:

$$\bar{W}^{(1)} = BR\,\bar{V}_B^{(1)} = \begin{bmatrix} .01 & .0075 \\ .0125 & .0075 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} .0175 \\ .0200 \end{bmatrix}$$

$$\lambda^{(1)} = \frac{1}{W_1^{(1)}} = \frac{1}{.0175} = 57.143$$

$$\bar{V}_B^{(2)} = \lambda^{(1)}\,\bar{W}^{(1)} = 57.143 \begin{bmatrix} .0175 \\ .0200 \end{bmatrix} = \begin{bmatrix} 1 \\ 1.1429 \end{bmatrix}$$

$$\bar{W}^{(2)} = BR\,\bar{V}_B^{(2)} = \begin{bmatrix} .01 & .0075 \\ .0125 & .0075 \end{bmatrix} \begin{bmatrix} 1 \\ 1.1429 \end{bmatrix} = \begin{bmatrix} .01857 \\ .02107 \end{bmatrix}$$

$$\lambda^{(2)} = \frac{1}{W_1^{(2)}} = \frac{1}{.01857} = 53.8502$$

$$\bar{V}_B^{(3)} = \lambda^{(2)}\,\bar{W}^{(2)} = 53.8502 \begin{bmatrix} .01857 \\ .02107 \end{bmatrix} = \begin{bmatrix} 1 \\ 1.1346 \end{bmatrix}$$

$$\bar{W}^{(3)} = BR\,\bar{V}_B^{(3)} = \begin{bmatrix} .01 & .0075 \\ .0125 & .0075 \end{bmatrix} \begin{bmatrix} 1 \\ 1.1346 \end{bmatrix} = \begin{bmatrix} .01851 \\ .02101 \end{bmatrix}$$

$$\lambda^{(3)} = \frac{1}{W_1^{(3)}} = \frac{1}{.01851} = 54.0250$$

$$\bar{V}_B^{(4)} = \lambda^{(3)}\,\bar{W}^{(3)} = 54.0250 \begin{bmatrix} .01851 \\ .02101 \end{bmatrix} = \begin{bmatrix} 1 \\ 1.1351 \end{bmatrix}$$

$$\bar{W}^{(4)} = BR\,\bar{V}_B^{(4)} = \begin{bmatrix} .01 & .0075 \\ .0125 & .0075 \end{bmatrix} \begin{bmatrix} 1 \\ 1.1351 \end{bmatrix} = \begin{bmatrix} .01851 \\ .02101 \end{bmatrix}$$

$$\lambda^{(4)} = \frac{1}{W_1^{(4)}} = \frac{1}{.01851} = 54.0250 = \lambda^{(3)}$$

Therefore,

$$\lambda = 54.0250$$

$$\bar{V}_B = \begin{bmatrix} 1 \\ 1.1351 \end{bmatrix}.$$

Calculate:

$$c = \sqrt{\lambda} = \sqrt{54.0250} = 7.3502$$

$$\bar{V}_R = cR\,\bar{V}_B = 7.3502 \begin{bmatrix} .05 & .05 \\ .1 & .05 \end{bmatrix} \begin{bmatrix} 1 \\ 1.1351 \end{bmatrix} = \begin{bmatrix} .7850 \\ 1.1525 \end{bmatrix}.$$

The resulting WEVs are, therefore,

$$V_{B1} = 1$$

$$V_{B2} = 1.1351$$

$$V_{R1} = .7850$$

$$V_{R2} = 1.1525.$$

Question 2

$$\text{Blue's UEV} = U_B(0) = \bar{V}_B^T\,\bar{n}_B(0) = \begin{bmatrix} 1 & 1.1351 \end{bmatrix} \begin{bmatrix} 100 \\ 25 \end{bmatrix} = 128.4$$

$$\text{Red's UEV} = U_R(0) = \bar{V}_R^T\,\bar{n}_R(0) = \begin{bmatrix} .7850 & 1.1525 \end{bmatrix} \begin{bmatrix} 100 \\ 25 \end{bmatrix} = 107.3$$

Blue is the superior force - it has the equivalent of 128.4 Blue type 1 weapons while Red has only 107.3. The initial force ratio is

$$F = \frac{U_B(0)}{U_R(0)} = \frac{128.4}{107.3} = 1.20.$$

Question 3

Blue is the superior force. Since both sides have set their break thresholds at 30 percent loss of strength, Red is the loser. When Red breaks, Blue's corresponding percent loss is determined by first solving equation (24)

$$\sqrt{\frac{1 - [1 - .3]^2}{1 - [U_B(t)/128.4]^2}} = 1.20$$

for $U_B(t)/128.4$. This leads to

$$\frac{U_B(t)}{128.4} = .8036.$$

So, Blue has suffered 1 - .8036 = 19.6% reduction in strength. Blue's strength, when Red breaks, is (.8036) (128.4) = 103.2, and Red's strength is (.7) (107.3) = 75.1.

Notice that if Blue had set its break threshold at something less than 19.6 percent loss in strength it would be the loser (assuming Red had set its threshold at 30 percent losses) even though it has the superior force.

Question 4

Equation (23) may be rearranged to yield the battle time, t, as a function of the fraction of the initial Red strength remaining. Performing the necessary algebraic manipulations, we arrive at

$$t = c \log_e \left[\frac{\sqrt{\frac{U_R^2(t)}{U_R^2(0)} + F^2 - 1} - \frac{U_R(t)}{U_R(0)}}{F - 1} \right].$$

Now, in the present example, $c = 7.35$, $F = 1.20$, and $U_R(t)/U_R(0) = .7$. Substituting these values into the equation leads to

$t \approx 2$ hours of battle until Red breaks.

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PLAYER-ASSISTED SIMULATIONS -- EMPLOYMENT TECHNIQUES AND LIMITATIONS

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DIVWAG is a computer-assisted division war game that simulates the major functions of land combat as well as air support of ground forces. DIVWAG will provide evaluation data to support US Army force planning and to assess the value of competing alternative systems within the context of realistic organizations and combat situations.

The DIVWAG system was designed to have the following capabilities:

a. Evaluating forces (a division plus slices of corps & army support) composed of maneuver units and their associated combat support and combat service support.

b. Producing detailed quantitative data for use in comparing the effectiveness of the forces.

c. Addressing high and mid-intensity conflict (nuclear and conventional war).

d. Addressing the surveillance and target acquisition functions and providing quantitative data that will permit evaluation of the contribution that varying sensor mixes provide to force effectiveness.

e. Addressing firepower to provide quantitative data that will permit evaluation of varying mixes of firepower means and demonstrate their contribution to total force effectiveness.

f. Providing a means for evaluating the effects of varying degrees of aerial, ground, and firepower mobility; and assessing the effect of mixes of mobility means on total force effectiveness.

g. Analyzing the command, control, and communications functions, including decision and communication delay times as well as intelligence processing.

h. Producing loss, expenditure, and consumption data for use in evaluating the capabilities of supply and transportation systems using varying supply rates as constraints on consumption or expenditure. The computerized portion of total DIVWAG system contains five closely interrelated but distinctly separate computerized processors, each of which plays a unique part in the game cycle. The five processors are:

(1) Constant Data Input Processor

(2) Orders Input Processor

(3) Period Processor

(4) Period Output Processor

(5) Analysis Output Processor

Prior to the development of the Division War Game Model (DIVWAG), the spectrum of analytical tools for evaluating the effectiveness of alternative forces could be generically partitioned into two sets: computerized simulations and manual and computer-assisted war games. Traditionally, the role of the computer in computer-assisted war games has been primarily bookkeeping and routine computation, with most decision-making being conducted by the players.

In contrast, DIVWAG contains systemic decision logic in a number of areas; for example, for analyzing and utilizing target acquisition information to control the allocation of firepower resources (artillery, attack helicopter and close air support sorties). The interface for controlling the major activities of units of interest is a special-purpose compiler. The compiler provides a robust language which permits handling of all key functional areas of the model and is capable of portraying realistically the contingency planning required for the conduct of division-level operations. The DIVWAG model represents an extension of the state of the art for analyzing combat operations by bridging the gap between high-resolution simulations and low-resolution war games in a realistic and balanced manner.

Combat results from a typical DIVWAG war game can be summarized on a map, showing Red force losses and Blue force losses by time interval, where the time intervals are related to specific Red force terrain objectives and Blue delay or defense lines. For example, a Warsaw Pact Combined Arms Army might be attacking a US H-series Mechanized Division, whose tactical plan involves covering force action from the border to Line A and delaying operations by the main force of the division at Lines A and B and covering force action between Lines A and B.

The times required by the Red force to move through these areas and lines could be given in four increments. These time delays and the indicated costs to the Red force (in tank losses and personnel losses) are major measures of the effectiveness of the Blue division during each phase. We

could also show costs to the Blue force, in tank losses and personnel losses.

These summary data are only the tip of the iceberg in terms of the variety and quantity of evaluation information produced by the DIVWAG war game (really a player-assisted simulation). We have detailed records of the specific cause of each casualty or item of equipment lost; such causes include close air support, armed helicopters, minefields, nuclear weapons, artillery (by caliber), and direct fire weapons (by type). We know when and where each loss occurred, and how the strength of each company or battalion (on the Blue or Red side) varied with time - for personnel and for each type of equipment item.

The computerized portion of DIVWAG is based on the following ten submodels: Ground combat; area fire/TACFIRE; air/ground engagement; ground-to-air attrition; Tactical nuclear; combat service support; Intelligence and control; airmobile; Engineer; Movement.

All firing of weapons in DIVWAG, whether direct fire or indirect fire, is based on a fairly realistic simulation of reconnaissance, intelligence acquired and target acquisition. Allocation of acquired targets to artillery, armed helicopters and close air support is done automatically by the intelligence and control submodel and carried out by the area fire/TACFIRE and air/ground engagement submodels. Terrain and weather constrain movement, reconnaissance, etc. and many operations are enhanced or constrained by engineer or supply activities.

I am discussing the virtues and capabilities of DIVWAG in order to set the stage for looking at some of its limitations. At the US Army Combined Arms Center we are developing techniques for getting around the most critical limitations and for enhancing and enriching the DIVWAG combat results. Since DIVWAG has limitations is it inferior to other models of this type and scope? That is a subject for another time. To raise some of the more general issues involved in selecting and using models, let's look at a hypothetical study -- a comparison of four alternative Blue forces - based on independent use of three different models (Figure 1). With each model it is assumed that the measure of effectiveness (terrain seized by Red) against the base force (e.g., US H-series Armored Division) is the standard against which the other three forces are to be measured. Using the DIVWAG model the reconnaissance - heavy force is best, followed by the firepower - heavy force. The Jiffy - Game model, a manual war game also at Fort Leavenworth, shows the firepower - heavy force as preferred, with the high mobility force second best. The firepower - heavy force is also number one when we use the mathematical model GEN IV and the high mobility force runs a poor third.

This example raises many interesting questions concerning methodology — dependence of study results on the model used, on the measure of effectiveness and on the time period of combat; percent difference versus

absolute differences and their relations with tactical mission accomplishment; in order to discriminate between alternatives should a model magnify differences or shrink differences; with a given model how large must differences be to be considered significant; should any large study be based on only one model?; the fact that most TRADOC studies have multiple objectives (not just a comparison of two or more forces) how can we achieve multiple objectives by the criteria we use in selecting a set of models (rather than just one model); and alternative techniques for joint employment of two or more models.

Our discussion today will concentrate on these last three questions.

Here are the six objectives of a hypothetical study (very close to those of a real TRADOC study for which the DIVWAG model is now being used);

1. Determine effectiveness of the new GLIPAR division.

2. Compare the GLIPAR division with the H-series mechanized division, in each of four missions (covering force, mobile defense, area defense, counterattack).

3. Identify lack of balance in the new division and suggest a better mix.

4. Determine the adequacy of each component.

5. Investigate the dependence of component adequacy on the mission.

6. Sensitivity analysis.

The new GLIPAR division is to be compared with the standard US H-series mechanized division, in each of four missions. Objectives 1, 3, 4 and 5 all refer to this new GLIPAR division, designed on paper and still subject to many changes in terms of total size, mix of fire support, direct fire weapons, target acquisition systems, etc. Objective 6, sensitivity analysis, refers to all five previous objectives, including the comparisons in Objective 2.

Let's look at a few typical results for Objective 2 and ask how sensitive these results might be to some of the major assumptions we must make. In Figure 2 only four of these assumptions are varied, to give a feeling for the extent to which arbitrary choices at the beginning (either by the study sponsor or the analyst) can unconsciously drive the comparison in one direction or another.

(These data would be based on some particular measure of effectiveness, such as the time required for the Red force to penetrate at least 50 kilometers). One goal of our pre-game analysis technique is to take a lot of our work out of the realm of the unconscious - to stop turning the crank on the computer long enough to think about what we are doing - and why.

The overall logic of our current approach, including pre-game analysis requires the following steps:

1. Study objectives and issues
2. Pre-game analysis
3. Impact estimation (relating study objectives to major assumptions)
4. Identification of support models required
5. DIVWAG game play (the central activity)
6. Side analysis based on the support models
7. Tentative conclusions
8. Sensitivity analysis
9. Final conclusions

A careful analysis of the study objectives and issues leads to rough values for major assumptions and also the systematic process of pre-game analysis - the central focus of which is impact estimation, and selection (or creation) of supporting models. These models actually influence some of the assumptions used in the DIVWAG game play and are also the bases for concurrent side analysis and later sensitivity testing. Finally it is interesting to see if the conclusions bear any relation to the study objectives.

Now we can get more specific about Impact Estimation. We resolve the study objectives into questions about force differences and other issues (about 50 in the present example). We decide which of the major factors and assumptions (more than 200) could have a significant impact on each of these issues and which of the sponsor-recommended assumptions are inconsistent with the study objectives.

The third step in Impact Estimation is to use our matrix of assumptions versus issues (to be illustrated in the next figure), as a guide in the creation of new models or selection of already-existing models. We list here six ways in which these models can be used to enrich and supplement the results achieved with the DIVWAG game play - the central nucleus of the analysis:

1. Select specific, realistic values for the major assumptions.
2. Sensitivity analysis.
3. Develop pseudo-conclusions, to help us focus the analysis.

4. Determine the extent to which an impact at a low level proliferates up to higher levels.

5. Resolve selected issues, for which DIVWAG might not have adequate resolution.

6. Determine intermediate data and interactions between measures of effectiveness to be extracted from DIVWAG.

In Figure 3 we have selected five issues from the GLIPAR study (about 10% of the total) and show the number of assumptions critical to each issue in each of six major categories.

These are all specific items such as "conditions under which the Red force will initiate the use of tactical nuclear weapons." A major problem is that if we set an assumption at one level to illuminate one issue this level might be completely inappropriate for shedding light on another issue. However it is completely appropriate to use judgment, as long as it is recognized as such.

We require at least the following seventeen types of mathematical models, since all of these operations are simulated by DIVWAG:

1. Ground combat
2. Artillery
3. Armed helicopters
4. Close air support
5. Air interdiction
6. Tactical nuclear
7. Air defense
8. Reserves
9. Replacements
10. Resupply
11. Air reconnaissance
12. Ground surveillance
13. Information flow
14. Airmobile operations

15. Engineer operations

16. Transportation, movement, barriers

17. Command and control

In addition various combinations are needed, such as tactical nuclear plus artillery plus ground combat.

Ultimately, in order to do the jobs we are asking -- pre-game analysis, side analyses, and post-game evaluation -- these models should incorporate many of the following features:

1. Mission

2. Doctrine and tactics

3. Situation
   physical environment
   enemy alternatives

4. Conditional decision-making

5. System performance

6. Constraints
   target acquisition
   supply
   weather
   communications

Most of our current models (and we have many) do not yet include such features explicitly - but we expect to work in this direction as time permits. We are also developing a general theory for deriving required model characteristics from specific study objectives -- i.e., a custom-tailored model design theory.

Now, referring back to our hypothetical GLIPAR study, we list six side analyses required and the specific models to be used.

1. Ground sensors	a. SURV II simulation
	b. Deployment sensitivity test
2. Maneuver unit org	a. DIVWAG ground combat model
	b. DIVWAG ground combat sensitivity tests

3. Air defense	a. DIVWAG ground-to-air attrition
4. Replacement doctrine	a. REP II model
	b. Break criteria sensitivity test
5. Close air support	a. DIVWAG pre-processing
	b. CAS I model
6. Nuclear	a. NUC III model
	b. NUC IV simulation

For number 2 (differences in maneuver unit organizations) we can use computer runs with the DIVWAG Ground Combat Submodel as well as extensive sensitivity tests already carried out with this submodel.

For air defense differences we will use sensitivity tests with the Ground-to-Air Attrition submodel of DIVWAG. REP II is a mathematical model developed for this purpose.

In the case of close air support there are the following six objectives of the close air support pre-game analysis: (Remember that this example study is primarily a force design comparison of alternative US Army divisions and that close air support is external support and not an explicit design variable).

1. Number of close air support sorties available

    Too large: dominate situation

    Too small: unrealistic burden on Army systems

2. Insights on adequacy of DIVWAG fire support allocation decision table (close air support, artillery, armed helicopters)

3. Insights on required balance between components of new force.

4. Discriminate between GLIPAR division and H-series division, in terms of organic fire support capability.

5. Answer "what if" questions, such as what if the enemy had employed twice as much close air support.

6. Test the DIVWAG ground-to-air attrition submodel.

Let me close by saying that at the US Army Combined Arms Center at Fort Leavenworth we are making a deliberate and systematic effort to use mathematical models, manual war games, player-assisted simulations - and any other [illegible] that will help us carry out efficient and valid force design studies.

MOE: TERRAIN SEIZED BY RED

TIME PERIOD: T+6 TO T+28

ALTERNATIVE BLUE FORCES	% ADVANTAGE OVER BASE FORCE ALTERNATIVE MODELS		
	DIVWAG	JIFFY	MATH-GEN I
1. BASE FORCE	0	0	0
2. RECON-HEAVY	20	10	27
3. HIGH MOBILITY	8	24	5
4. FIREPOWER-HEAVY	12	54	36

FIGURE 1. HYPOTHETICAL COMPARISON OF FOUR ALTERNATIVE FORCES USING THREE DIFFERENT MODELS

MAIN ATTACK AREA	RED REPL DOCTRINE	RED CAS S/DAY	% ADVANTAGE OF GLIPAR DIVISION	
			BLUE CAS	SORTIES/DAY
			60	30
WURZBURG	UNIT	20		-10
		40		
	INDIV	20	-5	
		40		
KASSEL	UNIT	20	+8	+3
		40		-15
	INDIV	20		-20
		40		

FIGURE 2. SENSITIVITY OF PERCENT ADVANTAGE OF GLIPAR DIVISION OVER H-SERIES DIVISION TO VARIATIONS IN MAJOR ASSUMPTIONS

GLIPAR STUDY ISSUE	NUMBERS OF CRITICAL ASSUMPTIONS					
	RED FORCE		BLUE FORCE			
	FORCE EMPLOYED	TACTICS	TACTICS	SYS PERF	PHYS ENVMT	OTHER
1. GROUND SENSORS	5	15	14	6	5	3
2. MANEUVER UNIT ORGANIZATION	8	14	12	4	4	2
3. AIR DEFENSE	6	12	15	5	7	3
4. AIRBORNE SENSORS	6	19	10	6	8	3
5. ARTILLERY	8	30	29	10	8	5

FIGURE 3. IMPACT ESTIMATION SUMMARY -- NUMBERS OF CRITICAL ASSUMPTIONS IMPACTING ON EACH ISSUE

STOPPING RULES FOR WAR GAMES OR COMBAT SIMULATIONS WITH EXPONENTIAL LIFE-TIMES

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(Autovon 870-3098)

ABSTRACT

Present war game simulations on computers must be run over and over again many times to get some idea of the outcomes which are sensitive to engineering changes or design objectives for military equipment. Thus, there is a need for stopping rules which will control risks of erroneous judgements in war game simulations or computer games. In view of a new formulation of Lanchester combat theory outlined in Reference [2], and recent related work, it is now possible to formulate stopping rules in terms of hypothesis testing procedures and reliability theory, when games are analyzed in terms of time-to-kill data. For example, it might be important to know whether Blue tanks armed with missiles would have a superior advantage against Red tanks armed with guns. In order to check this out, we might specify, for example, that in a combat engagement simulated on computers we would be interested in determining whether the chance of survival of Blue tanks would be as high as .90 as contrasted to that of being as low as .75. In this connection, we could set a risk of, say, 5% of rejecting the hypothesis that Blue's survival chance at some mission time of an engagement is .90 when true, and on the other hand set an assurance level of, say, 90% for rejecting this hypothesis when actually the true chance of survival of Blue tanks is only .75. Procedures are developed in this paper which determine criteria concerning how this may be accomplished for war game simulations with exponential life-times.

INTRODUCTION

A problem of considerable interest and importance in military operations research is that of providing appropriate stopping rules for war games and computerized simulations of combat. In the past, the practice has been that of running many simulations in order to study the variation in outcomes of a stochastic game and hence arrive at some idea of the confidence which might be placed on the results. A recent new formulation of Lanchester combat theory by the authors [2, 1972] makes possible the analyses of results in terms of random times-to-kill in battle, and hence in accordance with the statistical theory of reliability and life-testing, which has the advantage that stopping rules may be found for games with exponential life times simply by using the statistical decision theory of hypothesis testing.

ANALYTICAL SOLUTION

In their paper "A New Formulation of Lanchester Combat Theory," Reference [2], the authors derived the methodology of using statistical reliability theory to describe combat engagements or combat simulations. For a stochastic combat model, event times in battle (i. e. time-to-kill, time-to-incapacitate, etc.,) for key targets are taken as the more logical random variable to analyze, and the remaining forces on each side are dependent on time of engagement and can thus be described by some probability distribution in time. In many battles or simulations, the fraction of survivors at any time t, or that is the "reliability" of a combat force, may be described by the two-parameter Weibull distribution, since this distribution can be used to represent a wide variety of time-to-fail (or in this case, time-to-kill) probability distributions as shown in Reference [2]. The basic model is thus,

$$B/B_o = \exp(-\beta t^{\alpha}) \qquad B = B(t),\ \alpha,\ \beta > 0;\ t \geq 0 \tag{1}$$

$$R/R_o = \exp(-\rho t^{\delta}) \qquad R = R(t);\ \rho,\ \delta > 0;\ t \geq 0 \tag{2}$$

where B_o and R_o represent the initial numbers of Blue and Red combatants, or key elements or targets of interest, B and R are the numbers remaining on each side at any general time t after combat has begun; and β and ρ are scale parameters and α and δ are shape parameters for the Weibull distributions (1) and (2) that describe the "fighting power" of each side.

When equations (1) and (2) are used in conjunction with combat simulations that generate time-to-kill data immense savings in computer times could very likely be effected, since it becomes unnecessary to perform many iterations of the simulation in order to make valid statistical statements about the outcome. The parameters for the Weibull model may be estimated sometimes with sufficient accuracy from one simulation run or even from a truncated run as explained in Reference [2].

When conclusions are drawn from a truncated run, such as a preset, fixed number of casualties, the question naturally arises as to the number of observations or data points that are necessary in order to make a statistically accurate analysis. In other words, when a simulation is truncated, stopping rules are needed which will control the risks of erroneous judgements. This paper will develop such stopping rules by using hypothesis testing procedures and reliability theory, which can be developed easily when simulations of combat exhibit exponential life-times, i. e. for $\alpha = \delta = 1$ in (1) and (2). Since the mathematics of this paper are now fairly straightforward because the procedures developed closely follow the work in Reference [2], and recent related work by Grubbs [3, 1972], a compact example will be used as the vehicle for presenting the argument and related stopping rules for a truncated simulation.

Consider, for example, what acually may be a typical problem faced in the weapons acquisition process. Should Blue forces, for example, equip its new main battle tank (say, the XM1) with missiles or guns to effectively oppose Red's new battle tank, call it the R10, which is equipped with guns? Normally in a Blue versus Red tank battle, when Blue tanks are equipped with guns, we might say or assume that the Blue force would normally lose about 25% of its tanks on the average in the first 90 minutes of combat. (This 25% loss could have been predicted by using a previous detailed computer simulation model or verified from historical records, for example.) The proponents of the missile armament for the Blue XM1 might claim that the Blue force would only lose 10% of its tanks in similar battles for a mission time of 90 minutes. How, therefore, may we settle the issue?

The study team decides that if it can be reasonably sure that the fraction of XM1's surviving after 90 minutes of battle is in fact as high as 90% when armed with missiles, the change should be made. If, however, the Blue fraction surviving after 90 minutes appears to be close to 75%, the change would not be "cost-effective". The study team therefore, decides to test the following hypothesis:

H_o: The fraction of Blue XM1's surviving at mission time $t_m = 90$ minutes is .90, against the alternative hypothesis

H_A: The fraction of Blue XM1's surviving at mission time $t_m = 90$ minutes is only .75.

The team also decides that the acceptable risk of rejecting H_o when it is actually true should be about 5% (chance of a Type I error is $\gamma = .05$) and that an assurance level of 90% is required for rejecting H_o when it is false and H_A is true (chance of a Type II error is put at $\beta = .10$). Since there are not enough prototypes of the XM1 armed with missiles to place these tanks in an actual combat situation, nor is such desirable, a computer simulation of a typical battle with XM1's armed with missiles versus R 10's with guns will be run and the time-to-kill data taken, especially for Blue, in such a realistic simulation.

Since pre-tests with the simulation model and analyses of actual tank battles show that the life-times of tanks in combat can be expected to be exponentially distributed, the hypotheses to be tested can be restated as a special case of equation (1) i. e. as

$$H_o:\ B/B_o = e^{-t_m/\theta_o} = .9 \qquad \theta = 1/\beta \tag{3}$$

$$H_A:\ B/B_o = e^{-t_m/\theta_A} = .75 \tag{4}$$

With the mission time $t_m = 90$ minutes, the problem reduces to determining whether the fraction of survivors or the "reliability," $e^{-90/\theta}$, is .90 or is actually as low as .75; or that is whether in an engagement the mean-time-to-kill the XM1 armed with missiles is θ_o = 854.2 minutes, or is as low as θ_A = 312.8 minutes, these quantities being found from (3) and (4), respectively, for $t_m = 90$.

Our hypotheses now can be written equivalently as

$$H_o:\ \theta_o = 854.2 \text{ minutes}$$

versus

$$H_A:\ \theta_A = 312.8 \text{ "}$$

but our problem is that of determining the number of kills that we must observe before we can truncate the simulation, perform our test of significance, and control risks as indicated above.

Grubbs [3, 1973] has recently shown that for exponential life-testing and where $\theta_A < \theta_o$, the power function of the test, or the operating characteristic curves of the significance test given below in equation (11), implies that

$$\frac{\theta_o}{\theta_A} \simeq \frac{\left(1-\{1/9r\} + \eta_{1-\beta}\sqrt{1/9r}\ \right)^3}{\left(1-\{1/9r\} + \eta_{\alpha}\sqrt{1/9r}\ \right)^3} \tag{5}$$

where η_γ is the lower γ probability level of the standard normal distribution, $\eta_{1-\beta}$ is the upper β level and r is the required number of data or tank kill times required. Solving (5) for r, we find that

$$r = \frac{4(\mu-1)^2}{9[\mu\eta_\gamma - \eta_{1-\beta} + \sqrt{(\mu\eta_\gamma - \eta_{1-\beta})^2 + 4(\mu-1)^2}\,]^2} \approx \lambda^2/9 \qquad (6)$$

where $\mu = \sqrt[3]{\theta_0/\theta_A}$ and $\lambda = \frac{\mu_{1-\beta} - \mu\eta_\gamma}{\mu-1}$

Our <u>stopping rule</u> then is to analytically find r, the number of kills required before stopping the simulation, that will fit the operating characteristic curve as nearly as possible through the risks, $\gamma = .05$ and $\beta = .10$, for the acceptable and unacceptable true mean times-to-fail, $\theta_0 = 854.2$ and $\theta_A = 312.8$, respectively. Formula (6) above guarantees this.

For $\gamma = .05$, and $\beta = .10$ then, we find $\eta_\gamma = -1.645$ and $\eta_{1-\beta} = 1.282$.

Then we compute

$$\mu = \sqrt[3]{\theta_0/\theta_A} = \sqrt[3]{854.2/312.8} = 1.40, \qquad (7)$$

and

$$\lambda = \frac{\mu_{1-\beta} - \mu\eta_\gamma}{\mu-1} = \frac{1.282 - 1.4(-1.645)}{.4} = 8.9625 \qquad (8)$$

and finally

$$r \approx \lambda^2/9 \approx 80.3/9 \approx 8.9 \text{ or } 9 \text{ kills required.} \qquad (9)$$

Our stopping rule tells us that we need 9 Blue tank kills before we stop our simulation and perform our test at the risk levels $\gamma = .05$ and $\beta = .10$.

In order to complete our test, we run the simulation with some initial numbers, B_o and R_o, of tanks on each side (much greater than 9, say $B_o = 20$ or so), and until we have obtained 9 Blue tank kills, and record the times from the start of the battle at which each tank kills occurred. Next we compute our estimate of θ from Epstein and Sobel, Reference [1]:

$$\hat{\theta} = \sum_{i=1}^{r} t_i + (B_o - r)t_r]/r = [\sum_{i=1}^{9} t_i + (B_o - 9)t_9]/9. \qquad (10)$$

for the ordered kill times $t_1 \leq t_2 \leq \cdots t_r \leq \cdots \leq t_B$, the battle being truncated at r = 9 Blue tank kills. Since $2r\hat{\theta}/\theta = \chi^2(2r)$ is distributed in probability as Chi-square with 2r degrees of freedom, we will accept the hypothesis

$$H_o: \; B/B_o = e^{-90/\theta} = .90,$$

and hence that missiles are very effective, if

$$\hat{\theta} \geq \chi^2_{.05}\ (2r)/2r = \frac{(854.2)(9.39)}{18} = 445.6 \qquad (11)$$

If $\hat{\theta} < 445.6$ we reject the hypothesis that $B/B_o = .90$ and accept the alternative hypothesis that missiles are not so effective, and hence that fraction of Blue tanks surviving after 90 minutes of battle may indeed be as low as .75, in which case we would not buy the XM1 armed with missiles.

A similar analysis could be carried out, of course, for time-to-kill data on Red tanks.

The procedure studied herein for exponential life-times may be generalized to the Weibull distributions in (1) and (2), although two unknown parameters are involved. This is, therefore, a problem for further study.

SUMMARY AND CONCLUSION

We have given stopping rules for war game simulations with exponential life-times, and suggest that two important points should be noted in our analysis and the example above. First, the generation of time-to-kill or time-to-disable data from war games and combat simulations (which is not now frequently done) opens the door for a much more detailed study of combat using statistical reliability theory. In addition to the hypothesis testing procedures illustrated in the example, time-to-kill data enable us to use a wide range of reliability distributions to make point estimates or develop confidence bounds for the fraction of survivors at any point in time during the battle or engagement, Reference [2]. Estimating the parameters of combat (the parameters of the appropriate probability distribution) from time-to-kill data obtained from actual or simulated combat would also seem to more adequately account for the inherent randomness of combat then does estimating the describing parameters or "attrition rates" from the physical characteristics of the weapons outside the battle, or not taking proper account of two-sided conflict.

Secondly, many decision problems in the weapons acquisition process involve determining whether or not a system will operate as claimed or will function at a higher level of effectiveness than some existing weapon system. These types of problems often and naturally lead to some type of statistical hypothesis testing situation. If the effectiveness model used is a simulation that generates life-time data, the analysis is greatly simplified by allowing the use of the available reliability theory, for this leads to a rather straight-forward significance testing procedure. A fallout of the methodology described in the example is the stopping rule for determining the sample size or the number of data points (kill times) that are required before the simulation may be truncated and the test conducted at the prescribed low risk levels. This "stopping rule" is

simply the analytic solution for the number of kills required to fit the operating characteristic curve or power function of the test through the appropriate risk levels for a given ratio of survivors and the appropriate test parameters. It is seen, therefore, that the procedure may have considerable potential.

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THE ECONOMICS OF SIMULATION

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INTRODUCTION

This paper presents the methodology and preliminary results of a study of the economics of stochastic, discrete-event simulations. The point of view taken is that of the manager who, faced with a large problem, must ask two interrelated questions:

1. Should I use simulation as my method of solution?
2. If I simulate, how should I do so?

It has been our observation that for large-scale simulations--which are arbitrarily defined as those which require more than 2 man-years for development or run for more than 15 minutes on an IBM 360/50--the initial decision is often made quite casually. The thesis of this paper is that conduct of a cost-benefit analysis of the simulation aids in the decision-making process.

SYSTEM OVERVIEW

The common view of simulation costs is in terms of computer running costs, since these are readily identifiable from accounting information. However, these costs are merely the tip of the proverbial iceberg. Figure 1 shows that the simulation process has four stages: development, operation, modification, and repeated operation. The last two stages may be iterative or, if the project is aborted or not altered, may never be reached. Each of these stages can be considered in more detail. Figure 2 shows the activities performed within the development stage. This diagram is based on a synthesis of the breakdowns given by Applebaum (2), Emshoff and Sisson (3), Maisel and Gnugnoli (5), and Naylor et. al. (6). Within each of the activities (blocks), decisions are made by personnel at various echelons in the organization that affect or shape the resultant simulation. These detailed decisions, for example, involve the choice of language, in-house vs. job-shop, choice of computer, and level of detail simulated.

LITERATURE

A literature search to find relevant data and previous analyses yielded little information on this subject. Despite the large number of books and papers that deal with the technique of simulation, almost nothing has been written about the cost of simulation. The only major survey found was included in a report by Abt Associates (1) to the National Commission on Technology, Automation and Economic Progress

issued in February 1966. Only total cost and total time required for 50 economic and social models and simulations are given. A cost/benefit and cash flow analysis similar to that used for capital investments was presented by Fried (4) in a paper in Computer Decisions in 1971. Fried was concerned with computer projects in general rather than simulations. A PERT-like approach of three estimates for each component cost and payback and cash flow analysis to manipulate these cost estimates was the method used.

MODEL DEVELOPMENT

The model presented herein is based on the concept that the simulation development process is a systems development process. The system components, which were shown in Figure 2, interact to allow accomplishment of a set of requirements, namely the simulation objectives.

Each of the major components of Figure 2 can be further broken down into EVENTS. These events are usually accomplished in a specified sequence. Events often include participation by personnel from more than one department within the firm and require resources from more than one source. This can make selection of a particular course of action within an individual event difficult for a decision maker. Therefore, the events were divided into smaller parts, called END ITEMS, which are limited in scope to jobs that are the direct responsibility of one supervisor or individual.

Figure 3 shows an example of the detailed structuring performed. Simulation consists of four stages. The development stage consists of 10 major components. The first component, Problem Formulation, consists of two events: Problem Specification and Objectives Definition. The event, Objectives Definition, consists of three end items:

(1) Specify Objectives (2) Identify Outputs, and (3) Specify Relevant Variables.

A major part of the work involved making an exhaustive breakdown of the simulation process into these end items. Figure 4 shows schematically how this is organized and Figure 5 shows a representative breakdown for one component, Development of the Preliminary Model. It should be noted that the breakdown was deliberately exhaustive and that many simulations do not involve all of the end items presented.

DECISION FLOW MODEL

For any particular simulation, the exhaustive model can be reduced to a decision-tree diagram (see, e.g., Raiffa (7)) that encodes the sequence of steps and the associated costs anticipated for that problem. Furthermore, the alternatives can be specified explicitly so that the decision maker can see their implications systematically. Figure 6 shows the decision-flow model for the simulation development process.

The decision-flow diagram presents, in time sequence, the alternatives available and the information known to the decision maker as he progresses through the various paths. The decision-flow diagram includes decision forks and chance forks. At each fork, distinct alternatives, each with an associated expected cost, are available. Use of these

decision trees will not be explained here since the approach is the standard one of Decision Analysis. An explanation of the actions at each fork is:

Data Collection Fork. If input data are not available, they will have to be gathered in detail: by questionnaire, experiments, or analysis.

Preliminary Model and Verification. For most large simulations, small preliminary models are constructed to get a feel for the problem. However, this step can be eliminated, at some risk of incurring future costs.

Development Source and Language Selection. Will the program be coded in-house or under contract. Will a special purpose simulation language or a general purpose language be used?

Computer Model Validation. A choice has to be made as to what extent, if any, the computer model will be validated.

Validation Acceptability. This is a chance fork, since the attempt to validate may prove the model to be inadequate and require extensive revision.

Model Revision. If the model validation is unacceptable, then a decision must be made on the extent of the revision required.

Operation Source. Will an in-house or an out-of-house (contract) computer be used? Note that this decision will be affected both by the size of the computer program and the size of machine available in house.

Implementation. Once the simulation has been run, decisions must be made on how to implement the results.

To use the decision flow model, it is necessary to associate expected costs and probabilities with the individual alternatives. The Abt Associates study indicates that in their sample of 50 models, input data were available in 56% of the cases and the model validation results were acceptable without model revision in 50% of the cases. For a particular simulation, better probability information should be available.

From the point of the decision maker, the minimum cost path through the network is sought. This must be qualified in two ways. First, since large scale simulations require considerable time from initiation to completion, all costs should be discounted to make them comparable in present value terms. Second, arbitrary policy restrictions can eliminate some alternatives; for example, a lack of in-house programming help or a policy of doing all programming within the company. The finding of the minimum cost path is relatively straightforward (see e.g., Raiffa (7)).

APPLICATION OF THE DECISION FLOW MODELS TO TWO LARGE SIMULATIONS

To test the concepts just presented, the history of two large-scale

simulations were looked at. The historical approach relies on the memories of individuals. "Oral histories" of these two simulations were obtained from the individuals responsible for their development. Each individual responded to a prepared list of questions and his answers were tape recorded. The flow diagrams and the associated cost data were obtained from these tapes. These organizations are referred to as "B" and "R".

Case Example 1

Organization B was developing a simulation of a large-scale communication network that was planned for operation. The organization had no policy constraints that restricted the available alternatives. However, two decisions, made early in the planning, reduced the size of the tree. First, experimentation was believed to be the only acceptable way of obtaining needed input data for Decision Fork 1. Second, in-house programming in a special purpose language (Decision Fork 3) was selected. However, the in-house computer could not handle the language. Figure 7 shows the reduced decision-flow diagram of Organization B.

As shown in Figure 7, Organization B really had only two decision forks with more than one alternative. Because a previously formulated, small, manual network configuration provided the information generally obtained from a preliminary model, the decision maker decided against use of the preliminary model as such.

Computer model validation was undertaken, at least at a simple level. No attempts were made to apply sophisticated statistical validation techniques; however, computer results were compared to real world data. The comparison was judged to be sufficiently good so that the model was accepted as valid and was operated without revision. The path formulated by Organization B through the decision flow diagram, together with the associated costs, is shown in Figure 8.

Case Example 2

Organization R was developing a simulation of a transportation network that it operates. The organization's operating policies did not permit computer program development or computer time to be bought outside. All other alternatives were available, as shown in Figure 9.

The input data required for the simulation were available since the schedules and other operating data were those used by the firm in its day-to-day operations. A previously developed computer simulation model provided the information generally gained from a preliminary model, hence the development proceeded directly to the large model. The operating group responsible for the program selected a special purpose language rather than a general purpose language because of anticipated lower coding costs. Computer running costs were not taken into account since the computer was a "free good" as far as the operating group was concerned. There was sufficient confidence in the ability to represent the system. Thus, no model validation was undertaken. Figure 10 shows the final path through the network.

Discussion of Case Examples

In both case examples, a path was established through the network that represented what actually happened. It is not intended to say that these paths are optimal. In fact, a little analysis shows that lower cost paths could have been selected by Organization R. A critical decision is the selection of computer language. Selection of a language affects programming costs, validation costs, and computer running costs. Accordingly, an informal survey of several computer software firms was conducted which produced the following crude, approximate numbers:

	General Purpose Language	Special Purpose Simulation Language
Coding cost	2	1
Computer operating cost	1	8
Validation cost	1	1.5

Note that each line of the above table is independent and gives the relative cost for that item. For purpose of analysis, a 10% annual discount rate was used. Using the data shown in Figure 9 and the relative cost factors given above, the present worth of the coding + validation + operation costs were computed as follows:

	General Purpose Language	Special Purpose Language
Company B	$9900	$7500
Company R	$55700	$163,800

CONCLUSIONS

1. The presented decision-flow model enables decision makers to examine proposed simulation alternatives prior to committing resources.

2. The model was tested by two case examples based on oral histories.

3. An estimate of the cost of the analysis, if performed before the fact, will typically be of the order of one to two man-months. As shown for Company R, the potential savings in using a structured decision process can be much higher than this cost.

4. The narrative history technique appears to be a useful way for operations researchers to gather information.

5. The economics of simulation is a little understood subject and merits further investigation.

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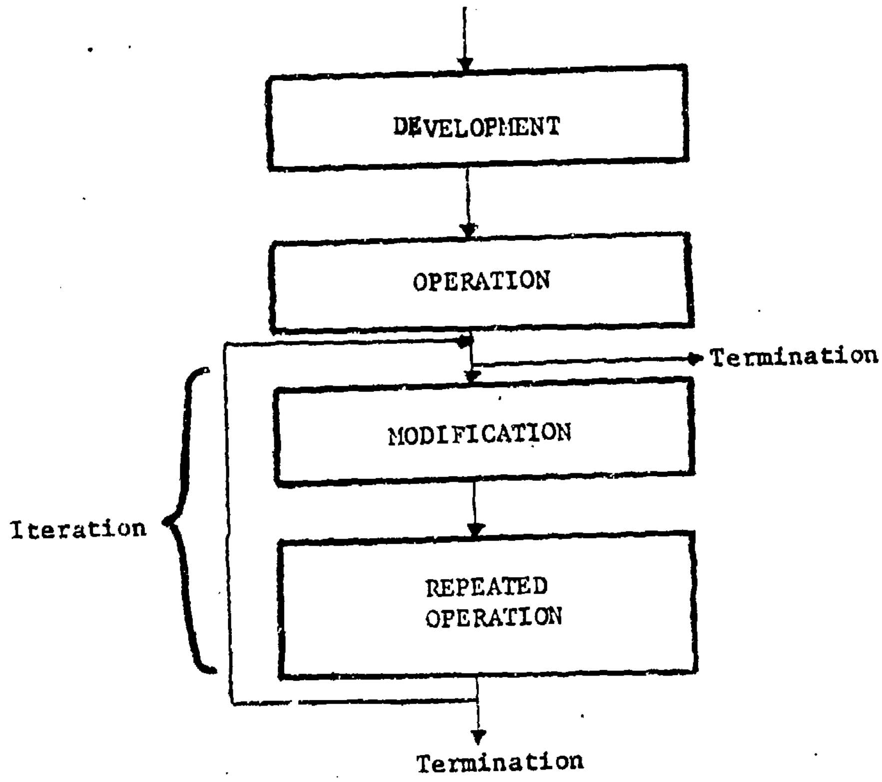

Figure 1. Four Stages of Simulation

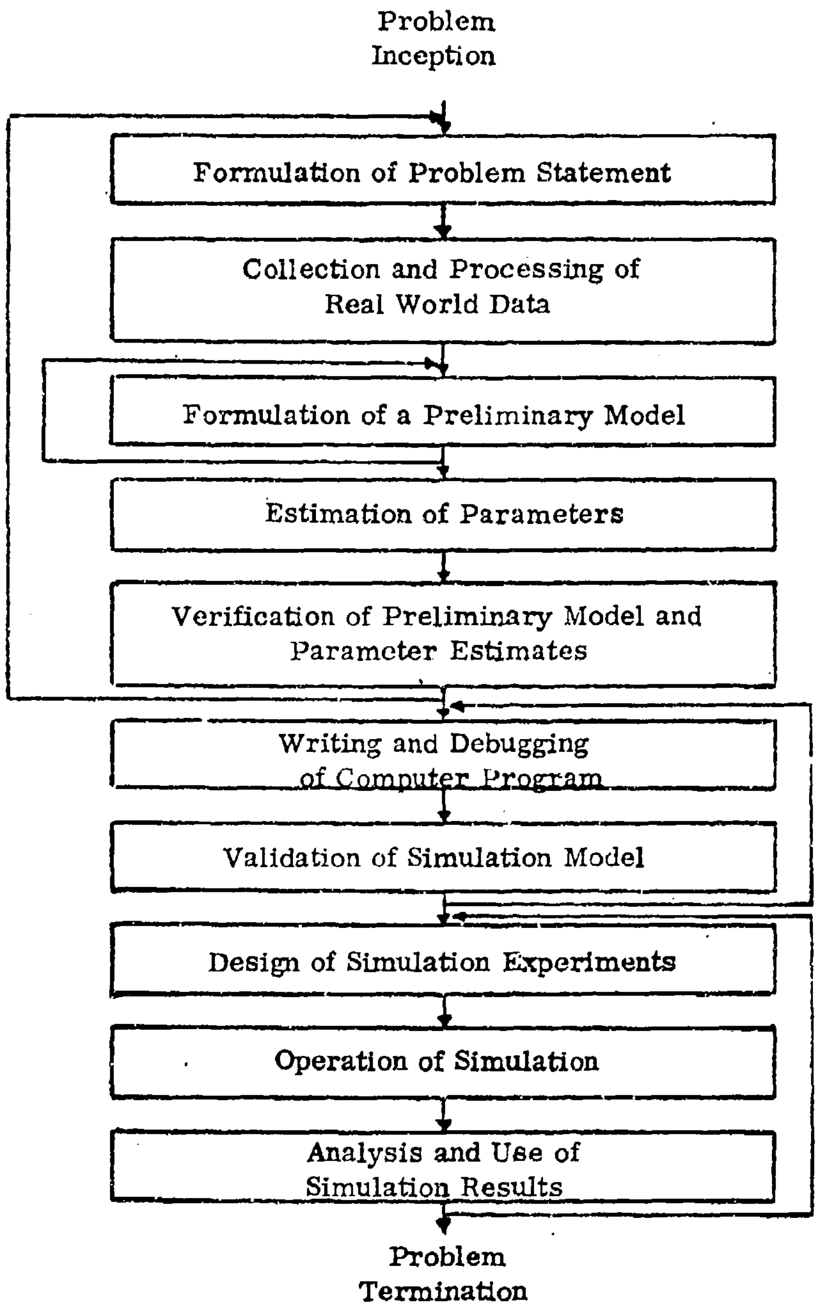

Figure 2. Flow Chart of Major Components of Computer Simulation Development Process.

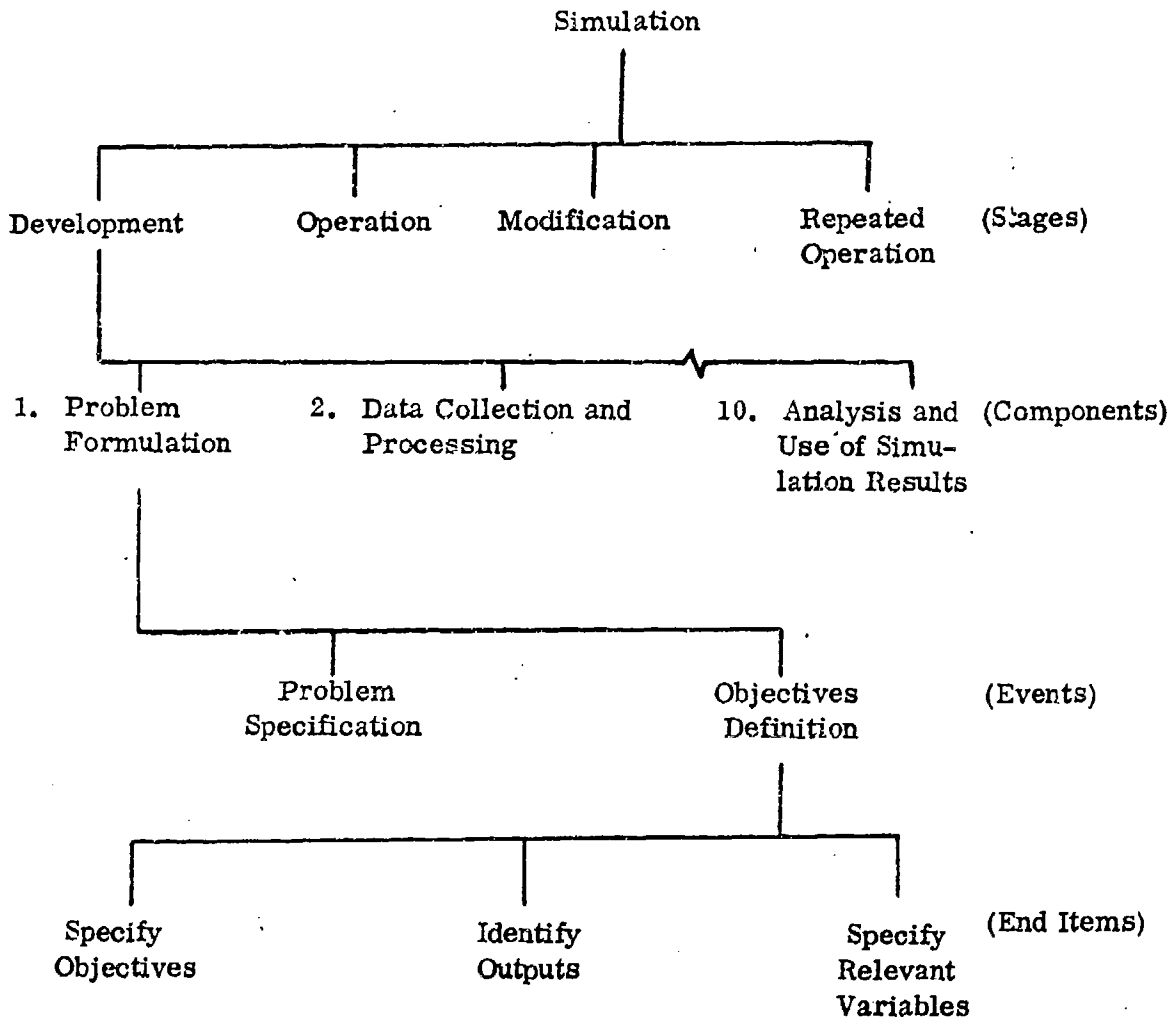

Figure 3. Structuring Process of Developed Model.

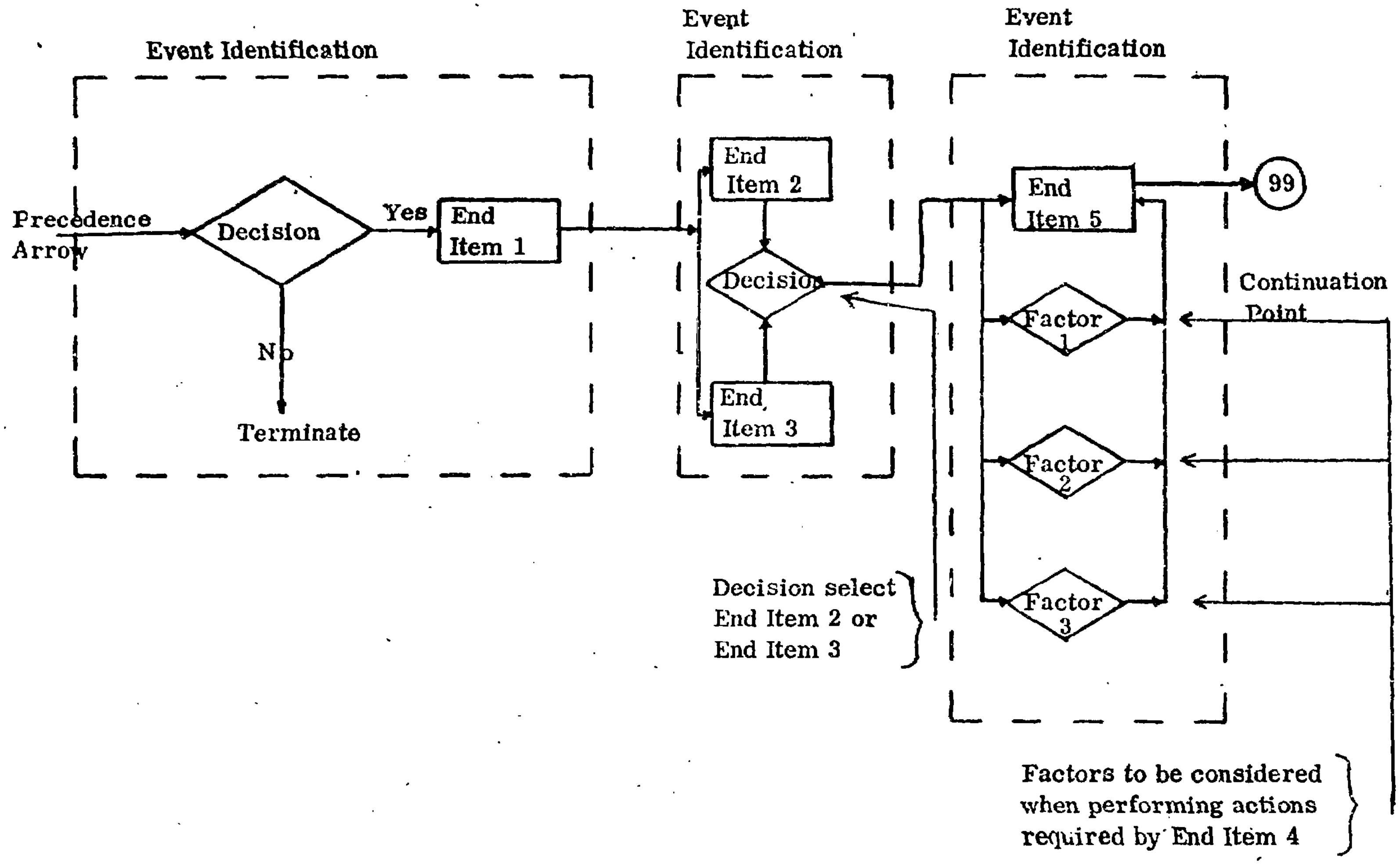

Figure 4. Diagram Format Explanation.

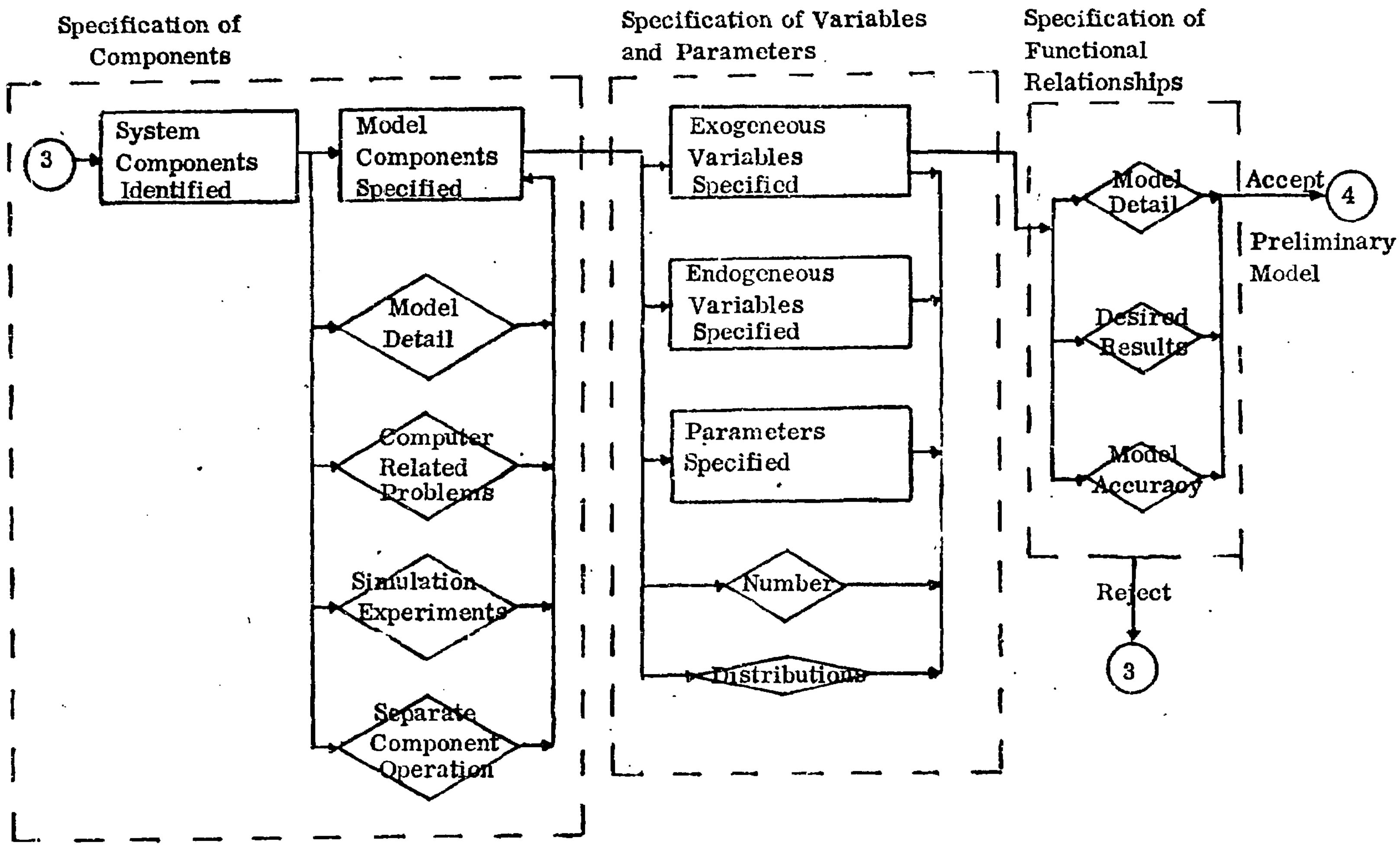

Figure 5. Development of the Preliminary Model--Component 3.

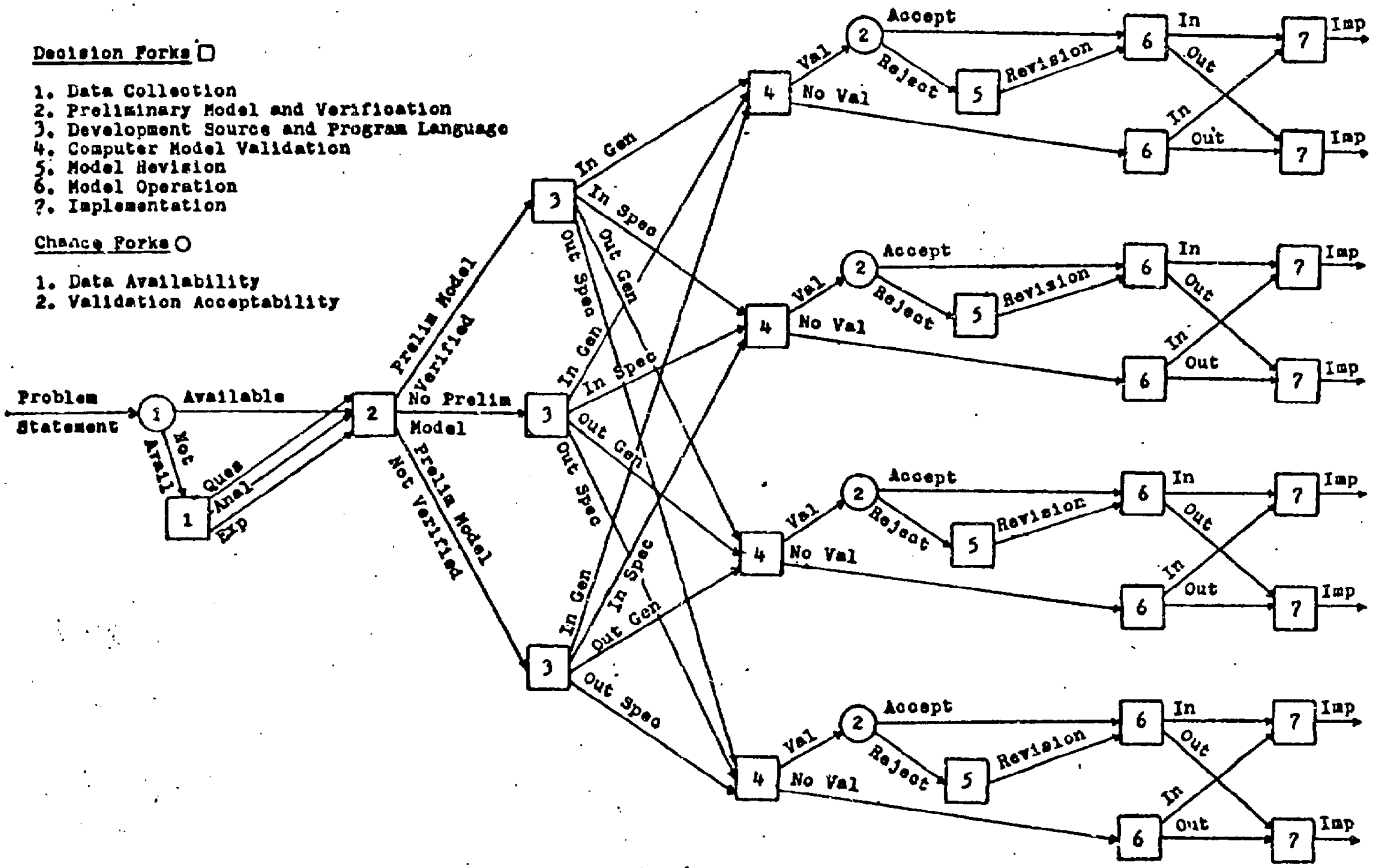

Figure 6. Decision-Flow Diagram for the Simulation Development Process.

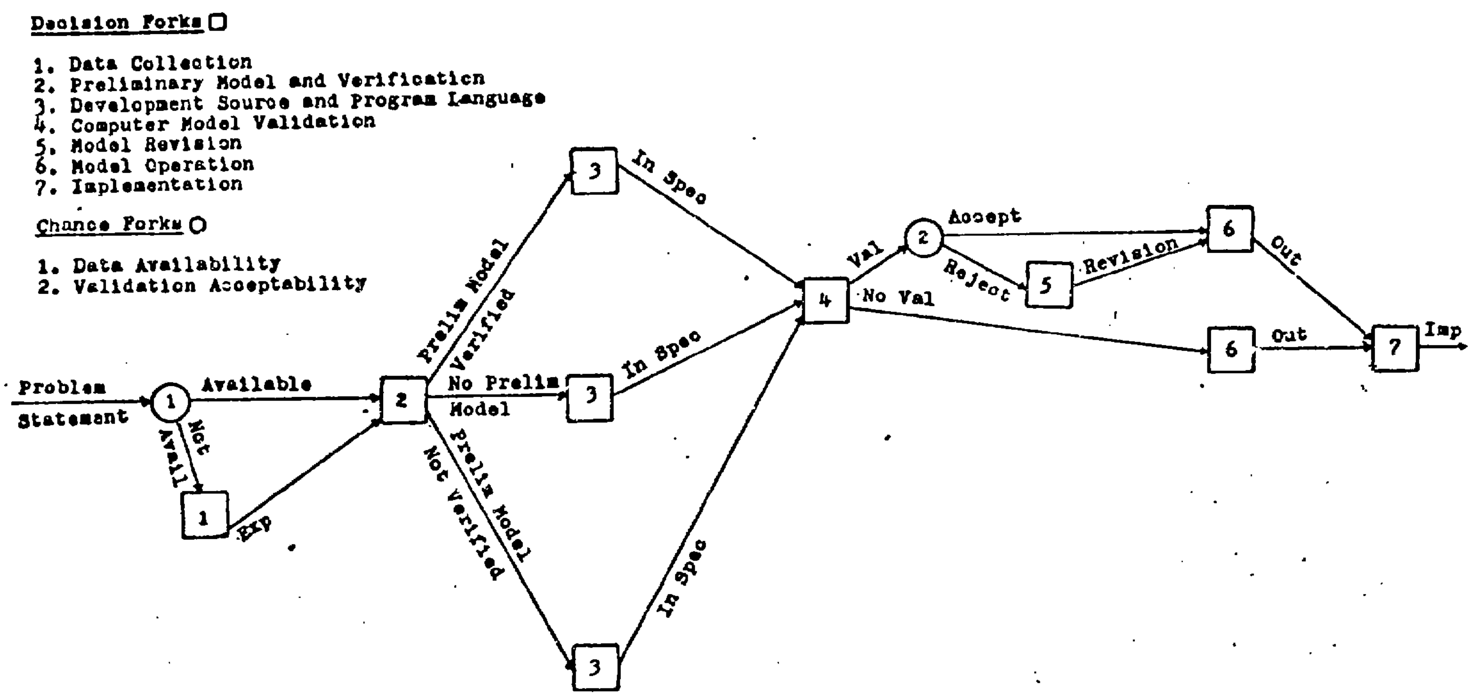

Figure 7. Reduced Decision-Flow Diagram of Organization B.

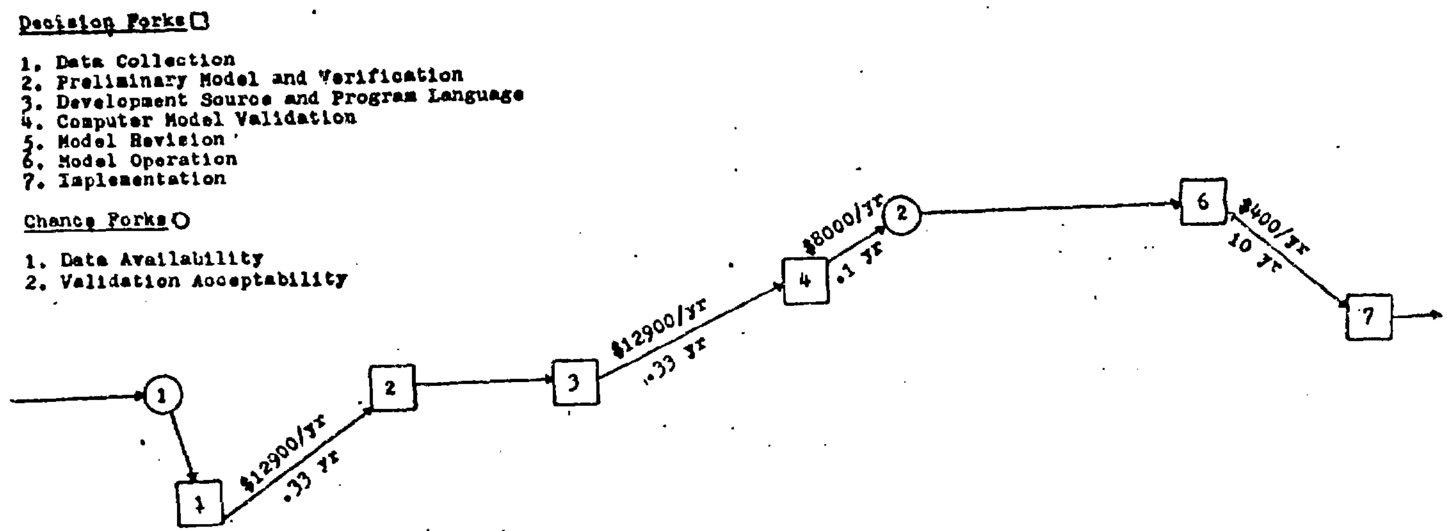

Figure 8. Organization B Path Through Decision-Flow Diagram.

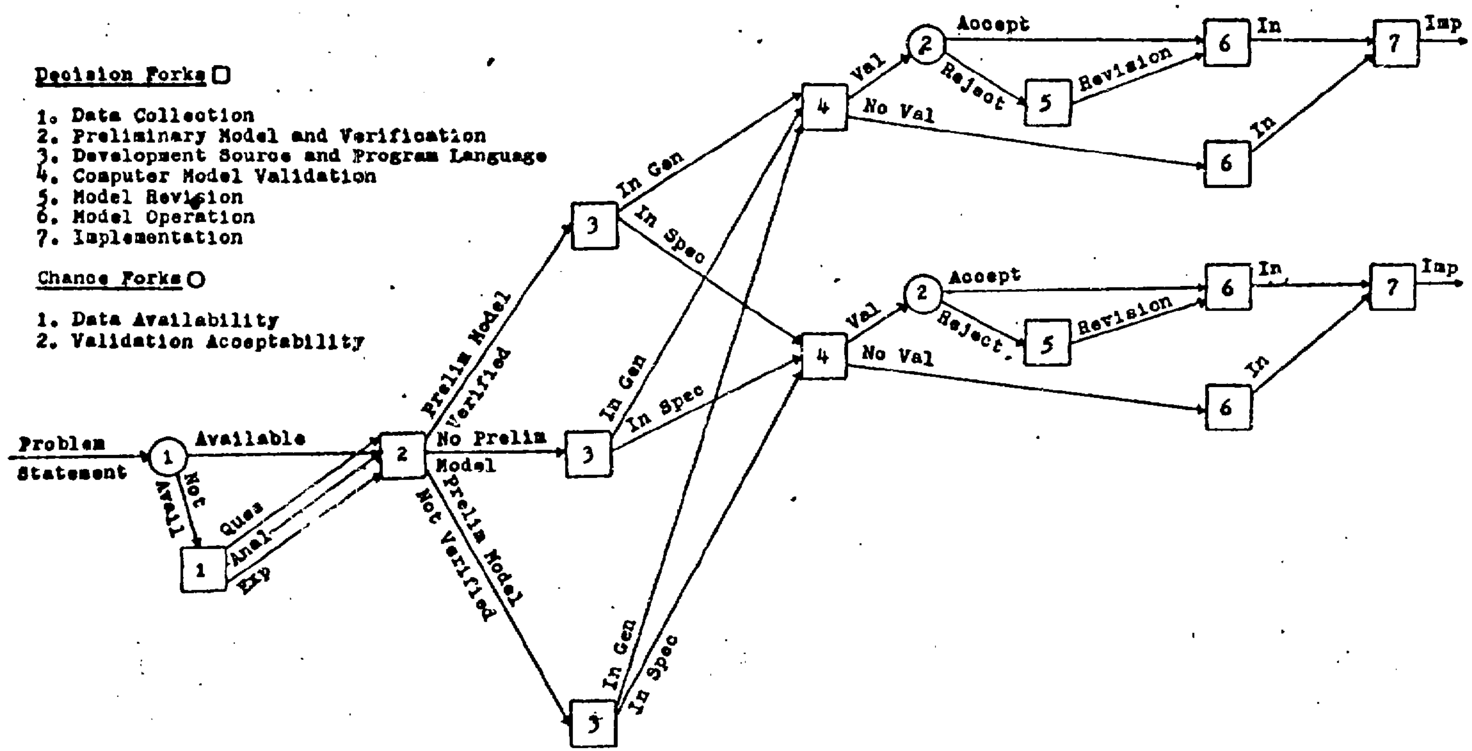

Figure 9. Constrained Decision-Flow Diagram of Organization R.

THE AUTOMATED ASSEMBLY OF SIMULATION MODELS

(This paper is UNCLASSIFIED)

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NTRODUCTION

Most operations research analysts have, at one time or another, anted to use a simulation model for the analysis of a problem being tudied. Research of available models usually reveals that the formu- ation needed hasn't been developed, or an existing model doesn't match he problem. Faced with this situation he could modify the problem to atch the available model, usually an unwise alternative, modify the vailable model, or develop a model to match the problem. The formula- ion and implementation of complex simulation models until recently has equired a lot of talent, a lot of effort and a lot of time. Modifying xisting models can be as costly as developing one. Many studies that ould have benefited from the application of simulation models by-passed hat route because of lack of time or resources.

This paper will describe a system that has recently been developed by the General Research Corporation which provides the capability to automate the assembly of simulation models. The system was developed for the US Army Logistics Doctrine, Systems and Readiness Agency, a Class II Activity of the Department of the Army Deputy Chief of Staff for Logis- tics. It has been tested and proven to operate satisfactorily.

BACKGROUND

Several years ago the Research Analysis Corporation (RAC—the predecessor to the Operations Analysis Division, General Research Corpor- ation) was awarded a contract by the US Army which included the task of developing a model of the US Army worldwide logistic system. The develop- ment study was given the acronym "MAWLOGS" (Model of the US Army Worldwide Logistic System). The task specified that the formulation was to be a simulation model to be used to "compare proposed systems with each other and with the current system to determine the relative merits of each system."

The research that preceded developing an approach to the modeling task revealed that the model had to be flexible in terms of functional range, system scope, drive, and level of detail and be structured along the lines of a node network system, which is characteristic of logistic systems. The logistic problems that would need to be addressed by such a model ranged from studying a single function within a small segment of the system to those of a worldwide nature, usually multifunctional in scope, and multi-item in detail. Thus, the model would have to be driven by demands for various types of logistic support, such as the supply of materiel and the provision of maintenance, originating at any echelon in the system, ranging from the troop unit level to the national level. Most of the problems identified during the course of the research focused

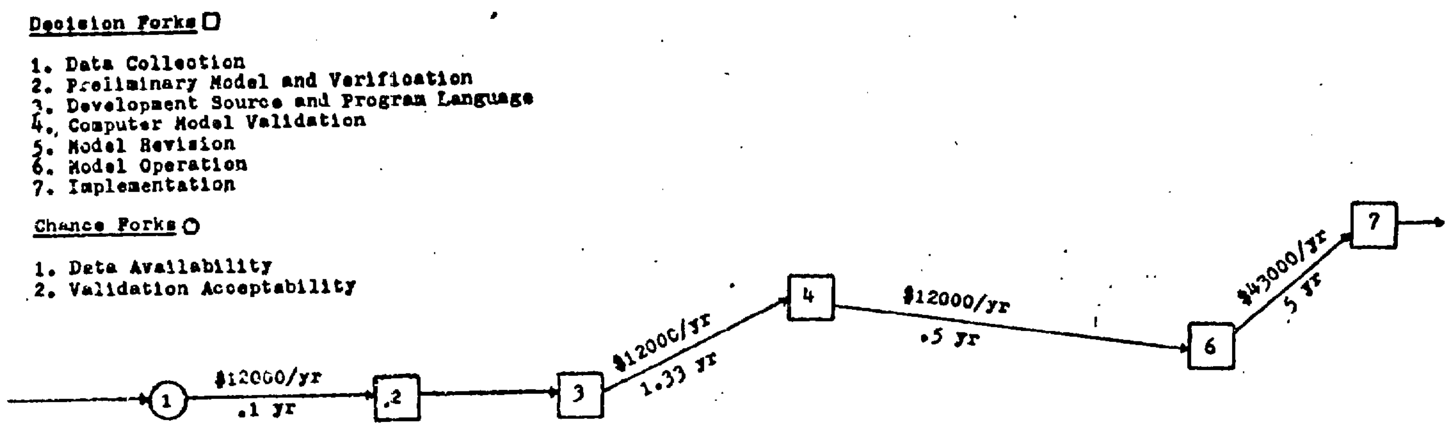

Figure 10. Organization R Path Through Decision-Flow Diagram.

on less than the total system, involved two or more interacting functions (e.g., supply, maintenance and transportation), and usually varied with respect to the desired level of detail. In addition, there appeared to be the need to treat one function, say supply, at one level of detail while treating the other interacting functions, such as maintenance and transportation, at different levels. A single model of the Army world-wide logistic system that would include these options appeared inefficient and indeed infeasible, considering available computers. Consequently, a flexible modeling system seemed a reasonable approach, and the task became one of designing a system for the rapid assembly of simulation models of specified scope and level of detail, designed to focus on the particular problem to be studied. Such a system has been developed and is currently operational at the General Research Corporation (GRC) facility in McLean, Virginia. In the near future, the Army is expected to develop the capability to apply the system at the Logistics Center at Fort Lee, Virginia.

The total system developed for the Army by GRC, called the MAWLOGS System, includes two computerized components in addition to those required for the rapid assembly of simulation models. These include a small set of programs designed to preprocess "raw" data for input to a model, called the Automated Input Data System, and a set of programs that process data output by a model, called the Output Data Postprocessor System. They basically support the application of a model and neither will be described in this paper. The complete documentation of the MAWLOGS System is expected to be disseminated by the Army near the end of 1973.

GENERAL DESCRIPTION

AUTASIM is the acronym for the Automated Assembly of Simulation Models. It is that part of the MAWLOGS System that creates simulation models. It represents a significant innovation in modeling methodology that should be of considerable interest to Army operations research analysts. The description of the AUTASIM system is the purpose of this paper.

The AUTASIM system consists of three elements: a Module Library, a Model Description Language and a Model Assembler program. The Model Assembler and the Model Description Language represent the primary innovations in creating simulation models. Development of a Module Library was not a trivial task, because it is broad in scope and actually required more time and effort to develop than the other two elements. Currently, it includes modular computer routines, each simulating a specific activity, and service routines that provide the conventional elements of a simulation model. Its form was dictated largely by the other two elements. Certain of the modules in the library—called verbs—constitute the vocabulary of the model description language. The Model Description Language is a methodology for describing the node network structure of a model and the activities that are to be simulated at the nodes and over the links in the model. The Model Assembler is a computer program which, given the description of the system to be modeled, will retrieve from the Module Library the required modules, link them together as prescribed in the model description, and produce a computer program of the system model.

SYSTEM CHARACTERISTICS

The AUTASIM system assembles simulation models of systems that can be described as node networks. Nodes are centers of activity and links are communication and transportation paths between nodes. The models can vary greatly in size and the scope of activities simulated. A model may contain one or more system nodes. The activities that can be simulated are represented by the modules in the Module Library. If an activity is needed in a model that is not represented in the Module Library, it is relatively simple to develop the required module or modules and add them to the library.

The activities simulated at each node in the system modeled are defined as an activity network of nodes and links, when more than one activity is simulated at a node. Each activity node can also be defined as a subactivity network. Figure 1 shows how a system can be represented as different levels of module networks. The content of other nodes may include the same modules but the network can be different. Modularity in this form provides great flexibility in defining the activities to be simulated at the desired level of detail. It also facilitates inclusion in a model of only those features that will accomplish the purpose of the model, with no extraneous logic and waste of core storage.

The AUTASIM system is fully automated. The Module Library is written on a tape file. Given the description of a model to be assembled, the Model Assembler program can assemble a model in a very brief period of time—five to ten minutes. This rapid model assembly capability also facilitates rapid changes to the activity content or system structure of a model, a characteristic often needed when comparing alternative concepts. The computer programs included in the AUTASIM system, the Model Assembler and the modules in the library, are written to the maximum extent feasible in USA Standard FORTRAN.

MODEL CHARACTERISTICS

A model produced by the AUTASIM system can be described as a discrete-event, dynamic simulation model. Most AUTASIM models are also stochastic; however, all elements of uncertainty in a model may be omitted by the model designer, which would then yield a deterministic simulation model.

The model programs generated by the Model Assembler are written in USA Standard FORTRAN.

Models assembled by this system have warmup and restart capabilities. The former shortens model running time before statistics collection is begun. The latter permits saving the status of a model at any point in simulation time for future model restart at that point in time. This permits the analysis of collected statistics at frequent intervals to determine their adequacy and can conserve computer usage.

Every model includes a complete statistics collection capability. The statistics the user wishes to collect and the form in which they are to be recorded are specified in the input data deck for model execution. A generalized reporting capability is also included in each model. The

OVERVIEW OF MODULAR APPROACH

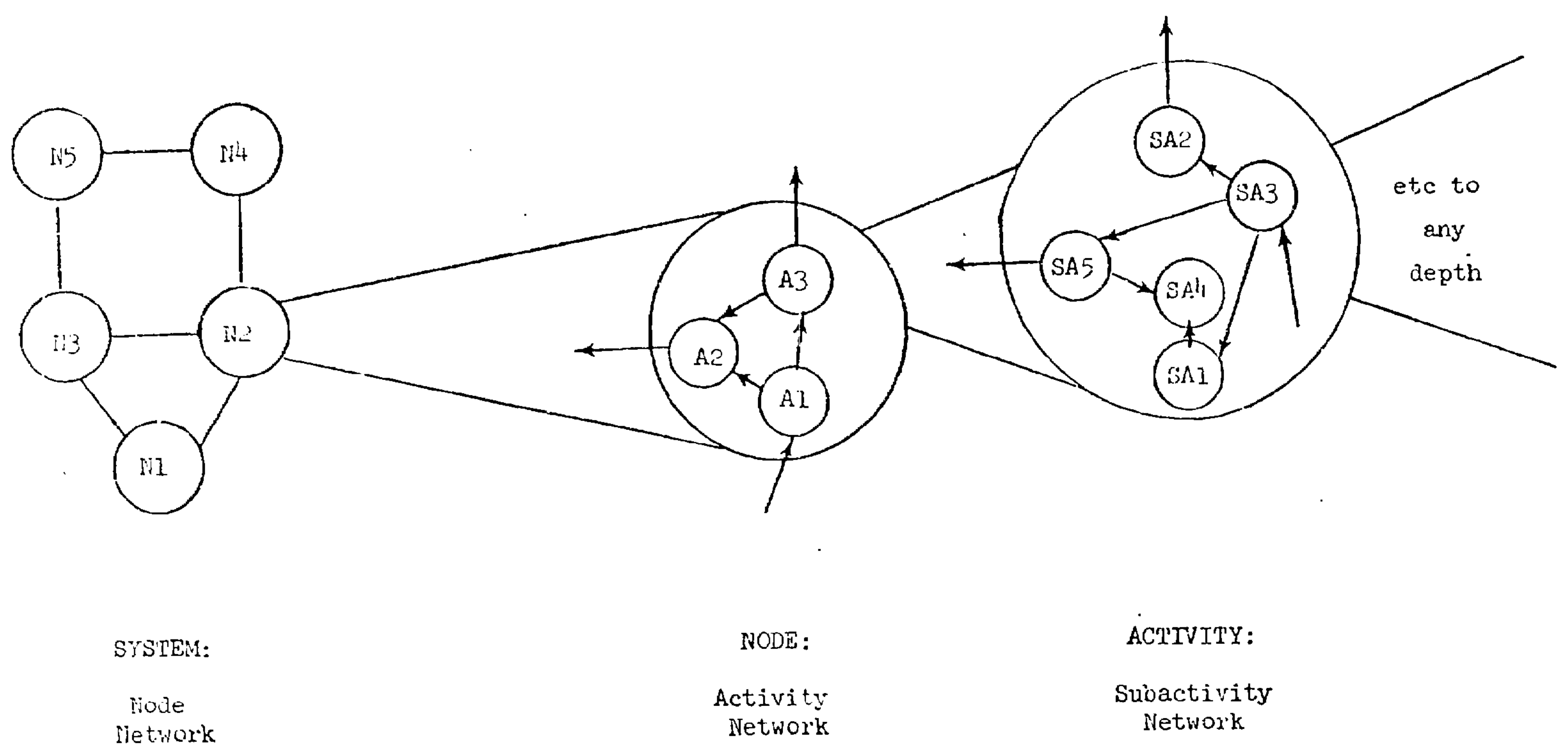

Fig. 1

user is free to specify when the model is assembled the reports he requires from the model. Statistics may also be collected in detail on a tape file for postprocessing.

As an aid in verifying the model, a trace capability is included. Prior to full-scale execution of a model, it is prudent to ensure that the model does, in fact, represent the desired system. This is usually a tedious and time consuming job, which is simplified by the built-in capability to trace events through all or parts of the system modeled.

MODEL DESCRIPTION

A model is described by using a symbolic language that facilitates the description of very complex node networks and is accepted by the Model Assembler program. The language consists of a "vocabulary" of module names, a set of delimiters, and a set of conventions for combining module names and delimiters to define the content and structure of a model. Experience has shown that this capability by itself is a very powerful tool. Multifunctional networks so complex as to be almost impossible to draw in the form of node network diagrams, can be described in the Model Description Language.

An illustration of the use of the language in describing a model will be given following the definition of some terms that have special meaning in the context of the AUTASIM system. These terms are listed below.

System	- a network of nodes connected by links.
Node	- a special block of programming logic which can be referenced in a model. An activity center.
Verb	- any block of programming logic which can be included in a model description.
Simple verb	- a block of FORTRAN code. The logic for simulating an activity.
Nonsimple verb	- a structured assemblage of simple verbs into a larger block of logic.
Module	- any block of logic which is contained in the Module Library; the set of modules includes verbs, service routines, and common data structure decks.
Parameter Slot	- a point in the logic of a verb at which control may be transferred to logic outside the verb.

The verbs in the Module Library are the vocabulary of the model description language. The content of a model is the set of simple verbs, or blocks of programming logic, which are specified in the model description. The structure of a model is the way the content blocks are interconnected.

The general structure of a verb is shown in Figure 2. The header information includes a reference to the routines called by the verb and the input data requirements of the verb. The program of a verb, like most programs, consists of logical steps or parts, with some of the parts contained in subprograms that are called from within the program. In the case of a verb, all the parts need not be included in the program or even be referenced by name, since a general external reference can be made. Parameter slots provide the capability of external references that need not be prespecified. A parameter slot can be inserted in the verb program at the point where logic outside the main verb logic may be applied to complete the function of the verb. A verb that deals with reordering stock, for example, could determine the reorder quantity by any of several policies. When the reorder verb program is written, the specific reorder policy need not be known and a parameter slot can be inserted at the place in the program where such a policy would be implemented. The person describing the model can therefore specify the policy he wants implemented by filling the parameter slot with a reference, probably another verb, that simulates the desired policy. This modular form of programming provides great flexibility and minimizes the size of verb programs. The simple multinode system diagram shown in Figure 3 will be used to demonstrate how the model description language is used to describe a system. The diagram shows a five-node system. Each node must be given a name or number of from one to five characters. Recall that each node is an activity center where one or more activities are simulated. The block in Node 1 labeled A represents the activities to be simulated at Node 1, the blocks labeled A, C and D, those to be simulated at Node 2, etc. The precise activities represented by A at Node 1 and their connection with Node 2 are described in the Model Description Language as shown below.

```
NODE1. VERBA (1 = VERBB $
              2 = VERBC (1 = VERBB)),DELAY(P=3),*NODE2 $
```

This description of Node 1 states that it contains the activity represented by VERBA; that at the point in the execution of the logic of VERBA where Parameter Slot 1 is encountered, control is transferred to VERBB; that after the execution of the entire logic of VERBB, control is returned to VERBA; that after the execution of some more logic of VERBA where Parameter Slot 2 is encountered, control is transferred to VERBC; that at the point in the execution of VERBC where Parameter Slot 1 is encountered, control is transferred to VERBB; that after the entire logic of VERBB is executed, control is returned to VERBC; that after the remaining logic of VERBC is executed, control is returned to VERBA; that after the remaining logic of VERBA is executed, control is transferred to verb DELAY, which has been directed to find a value in probability distribution number 3 for the delay parameter in that verb; that after verb DELAY is executed, control is transferred to Node 2. Schematically this description would appear as shown in Figure 4.

The significance of this illustration is that it demonstrates how one can describe a model including very complex interrelations among blocks of logic with time interdependencies among system processes in relatively simple form. It also demonstrates the flexibility in varying logical procedures available to the person describing a system to be modeled. Admittedly he must be very familiar with the system to be

VERB STRUCTURE

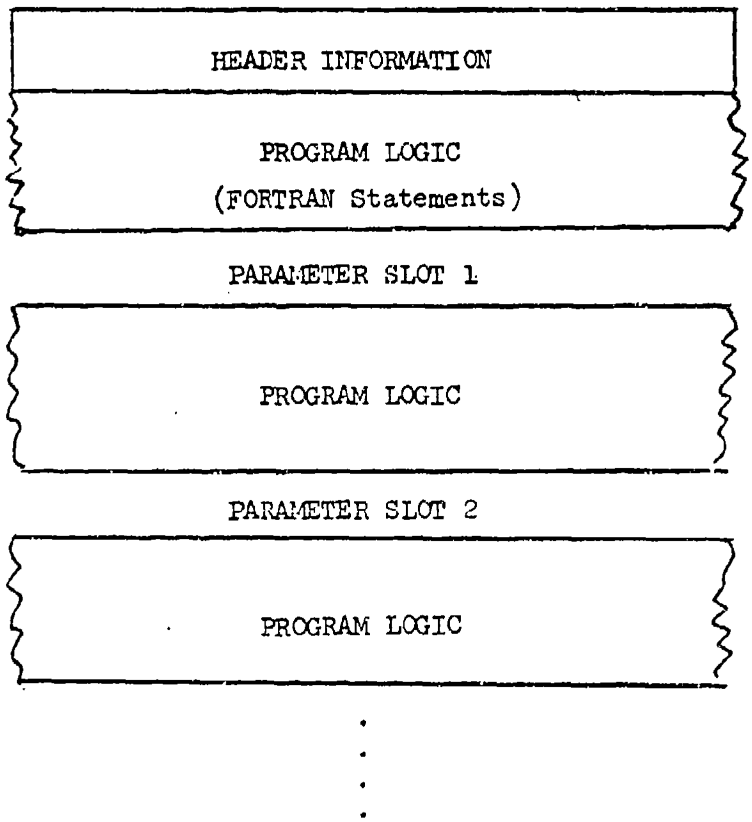

Fig. 2

ILLUSTRATIVE NODE NETWORK SYSTEM

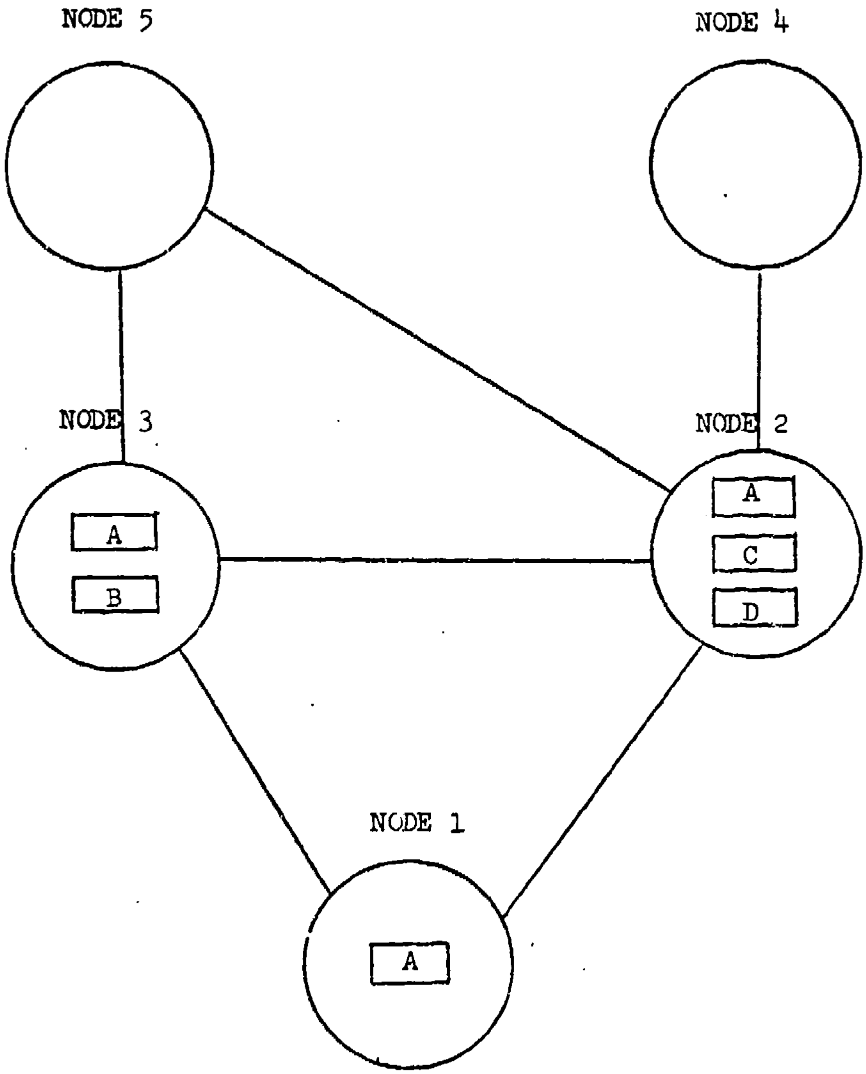

Fig. 3

SCHEMATIC REPRESENTATION OF FLOW CONTROL

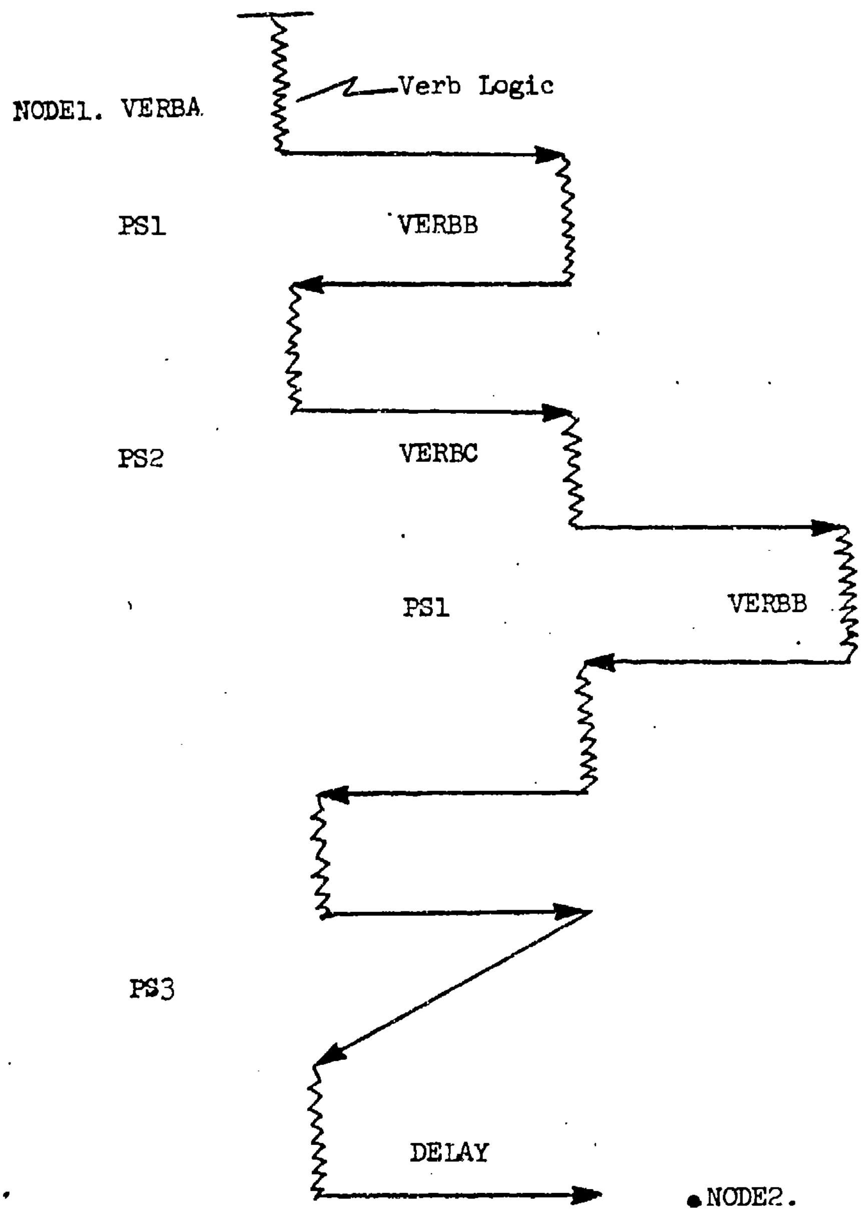

Fig. 4

modeled, which is essential for any analyst describing a model, and quite intimate with the contents of the Module Library.

Model descriptions can be simplified by the use of nonsimple verbs. Commonly used combinations of simple verbs can be formed into nonsimple verbs and be stored as such in the Module Library. The earlier example of verb VERBA in Node 1 can be constructed as nonsimple verb NSVA1 and be defined as shown below.

NSVA1: VERBA (1 = VERBB $ 2 = VERBC (1 = VERBB)), ** 1

The key point is that NSVA1 has been defined as a particular pattern of simple verbs VERBA, VERBB and VERBC and can be used in model descriptions. The description of Node 1 shown earlier can now be written as follows:

NODE1. NSVA1 (1 = DELAY(P=3), * NODE2) $

The reference to nonsimple verb NSVA1 in the model description would cause the Model Assembler to include its structure in the model. One or more verbs used to define a nonsimple verb may themselves be nonsimple, to any depth. Every nonsimple verb however must ultimately be expandable into only simple verbs, since, among verbs only simple verbs may contain program statements that are executed.

MODEL ASSEMBLER

The Model Assembler is a computer program that, given the description of a model written in the Model Description Language and access to the Module Library, will retrieve from the library the required modules, generate linkage routines interconnecting them according to the model description, and output a complete computer program of the model. An additional input for a model being assembled is a set of dimension values that are used to set the dimensions of the data storage arrays in the model program.

The model assembly process is shown in Figure 5. The assembler scans the model description one node at a time, building a list of the designated verbs. Any nonsimple verbs are then expanded. Modules referenced by the verbs on the list are then added to the list. At the end of a node scan, linkage routines are created which connect the verbs in the specified manner. This process is repeated for each node in the model description.

After all nodes are scanned, the modules required in the model are retrieved from the Module Library and the module and linkage source code are combined. Then a list of all common data structure decks required by these modules is made, the decks are retrieved from the Module Library, and their dimension values are set.

The Model Assembler outputs include the complete model program written on a tape file, a listing of the model program, an expanded model description, a list of the modules in the model, and a list of the model input data requirements. The expanded model description includes the

MODEL ASSEMBLY PROCESS

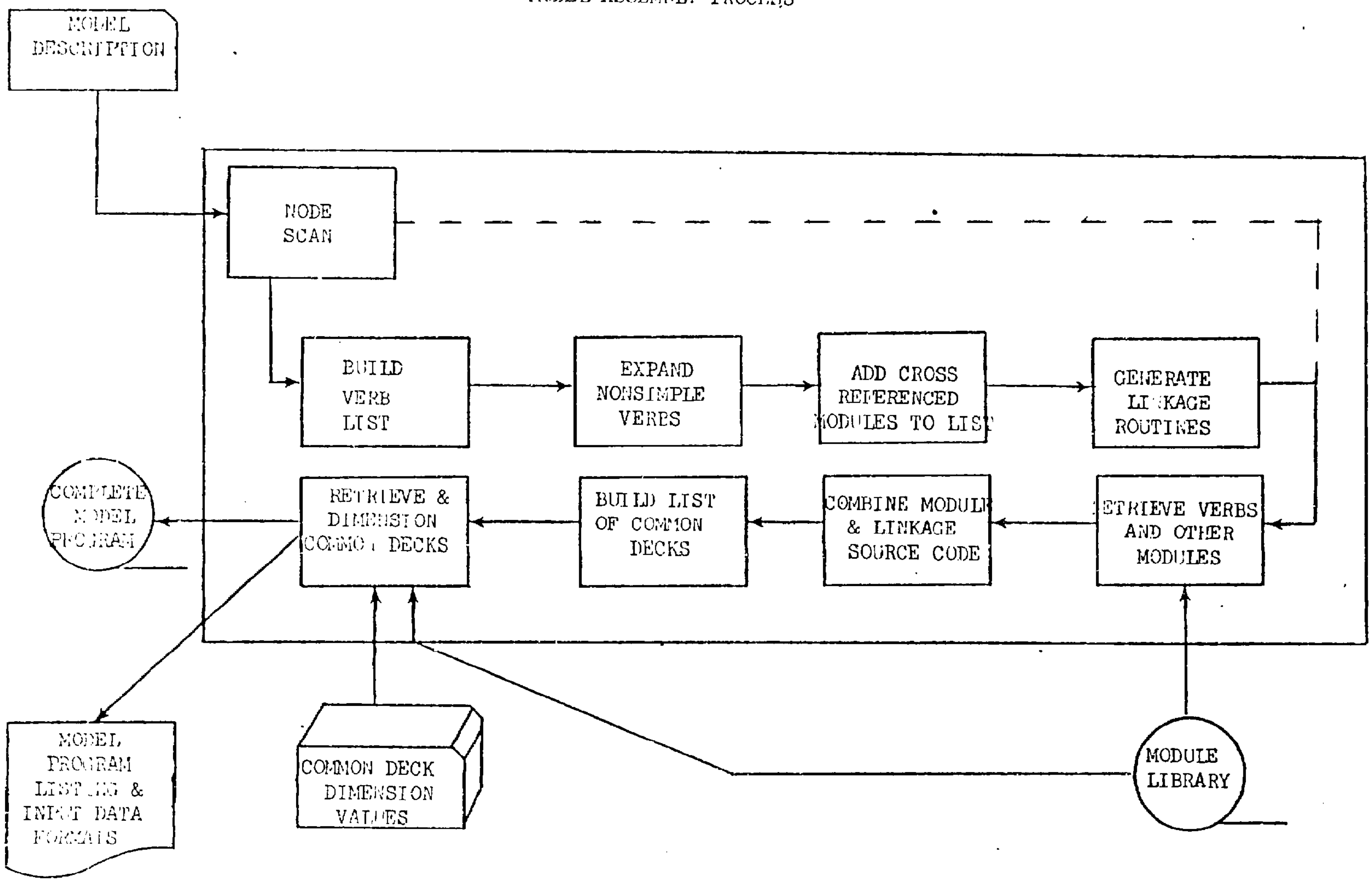

Fig. 5

description as input plus the expansion of all nonsimple verbs to show their structure. The list of input data requirements is an important and valuable output of the Model Assembler, because the inputs for a model depend on the verbs included in the model. Each model therefore requires a unique set of inputs. This listing is a great help to the model user in preparing the inputs for model execution.

Figure 6 shows how the model input requirements are described. The inputs are listed by node and within node by module in the order in which the cards are to be assembled for input. The input requirements for a module include a description of each data element, the card columns in which the data are punched, and the format for the data.

The Model Assembler program is written in FORTRAN, occupies about 32,000 words of core storage on the Control Data 6400 computer and requires nine files. Model generation times have ranged from five to ten minutes of central processor time on a Control Data 6400 computer. Small models of six to eight nodes could require the lower bound of the time, while large models of about twenty nodes could require the upper bound of time.

It should be noted that since the Model Assembler scans one node at a time, there is no practical limit on the size of the models that can be generated. Thus the assembler could produce models that would exceed the core capacity of generally available computers.

MODULE LIBRARY

A brief overview of the Module Library is needed to complete the description of the AUTASIM system. The general structure of the library is shown in Figure 7. As stated earlier it consists of verbs, service routines and common data structure decks. The verbs currently in the library are those required to assemble models of logistic systems. This part of the library is expected to grow as new verbs are developed and added to simulate activities foreign to those simulated by the current verb library. The service routines represent a complete package required for almost any model that could be assembled by this system. Common data structure decks might be expanded as new verbs are added. A point to be made is that the addition of new verbs required by models that [illegible] not be assembled from existing verbs is a trivial task compared to building a complete model in the conventional manner.

The figure does not represent the true proportion of verbs, service routines and common decks. There are about 400 modules currently in the library. Approximately 220 are verbs, 160 are service routines and 20 are common data decks.

It was decided by the Army that the initial set of verbs to be developed would be those necessary to simulate the Army material support system with supporting transportation and communications. The materiel support system can be defined as that part of Army logistics by which fleets of end items are supplied to and maintained in using units. The content of the verb section of the module library reflects that decision. Figure 8 shows the four families of verbs currently in the library.

MODEL INPUT DATA REQUIREMENTS
PRODUCED BY MODEL ASSEMBLER

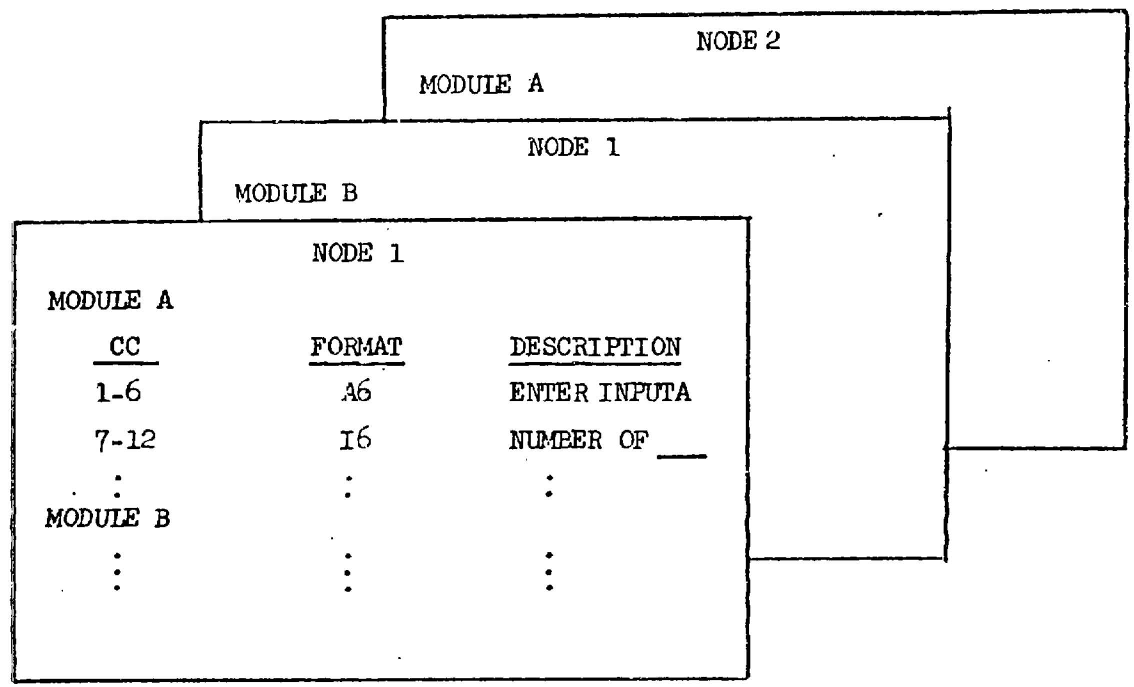

Fig. 6

MODULE LIBRARY STRUCTURE

VERBS

NEW VERBS

SERVICE ROUTINES

- Executive Routines
- Program Control Routines
  - Time Flow
  - Logic Flow Stacks
- Data Accessing Routines
  - Temporary Data
  - Permanent Data
  - Random Variables
  - Statistics Collection

COMMON DATA STRUCTURE DECKS

Fig. 7

EXPANDED VIEW OF VERB SECTION
OF MODULE LIBRARY

FIELD MAINTENANCE AND SUPPLY FAMILIES

- Supply
- Direct Exchange
- Maintenance
- Rebuild
- Float

WHOLESALE SUPPLY AND MAINTENANCE FAMILIES

- National Inventory Control Points
- Supply Depots
- Maintenance Facilities

TRANSPORTATION FAMILIES

- Aggregate Transportation
- Detailed Transportation

COMMUNICATION FAMILY

Fig. 8

The field maintenance and supply families simulate the material support system below the wholesale level. These verbs simulate the key supply and maintenance activities associated with the support of troop units and fleets of equipment at the troop unit level. They include the generation of maintenance demands, the repair, rebuild and salvage of end items and reparable components, and the supply of end items, components and repair parts. The level of detail is that of individual transactions, such as maintenance demands, supply requisitions and individual shipments. Statistics are collected on fleet availability, supply response, workloads, resource levels, resource utilization and time delays.

The field supply and DX activities simulated include demand processing, replenishment ordering, receipt processing, demand forecasting and revision of inventory policy parameters. The major maintenance activities simulated include diagnosis, skill assignment, parts assignment and repair. Related activities include generation of demands, ordering of parts, and issues from maintenance floats. The main difference between field maintenance and field rebuild is that in field maintenance unserviceable items are repaired one at a time, while in field rebuild they are repaired in batches.

In wholesale supply and maintenance the available levels of detail are similar to those for the field. That is, activities are simulated at the level of individual transactions, such as single requisitions, procurement orders, and supply control studies for individual items. The wholesale system is viewed as consisting of NICPs, supply depots and maintenance facilities.

Both of the transportation families simulate the movement of individual shipments over links that connect transportation terminals. Up to six different modes of transportation can be simulated in the same model. These are air, sea, rail, highway, inland waterway and transshipment from one mode to another. In the aggregate family only the movement of items with a combination of delay times for terminal operations is simulated. The detailed family simulates the consolidation of shipments into vehicle or carrier loads and the movement of the carriers through the network, assigning docks at terminals, maintaining arrival and departure queues, and diverting carriers from overloaded terminals.

The communications family is designed to simulate delays encountered in processing and forwarding individual messages through communication terminals. Various forms of message scheduling are available.

In summary, the Model Description Language has been described. It facilitates the description of very complex node network systems, multifunctional and multiechelon in nature. It is a very powerful modeling tool. The Model Assembler applies this language in assembling discrete-event dynamic simulation models. Given the required modules, it can assemble models in five to ten minutes of CP time on a Control Data 6400 computer. The combined capabilities of the Model Description Language and the Model Assembler represent significant technological achievements that should lead to greater use of simulation models in operations research studies. The content of the current Module Library provides the capability

to model a wide range of logistic systems at several levels of detail. It can easily be expanded to embrace additional functions or different levels of detail for functions currently represented. The operations research analyst looking for a model to fit his problem should consider the AUTASIM system. It is not a model in itself, but a system for the rapid creation of a wide range of simple or complex simulation models.

In closing it is appropriate that contributions to this paper by two colleagues at GRC be acknowledged. They are Dr. Robert T. Burger and Mr. Howard A. Markham. They and Mr. Thomas M. Lisi, inventor of the model assembly language and developer of the initial formulation of the model assembler program, are largely responsible for the development of AUTASIM.

A GENERAL COMPUTER PROGRAM FOR USE IN DETERMINING TRACK WIDTH PLOW-MINEFIELD EFFECTIVENESS CRITERIA

Mrs. Beverly D. Briggs

USAMERDC

ABSTRACT

The U.S. Army Mobility Equipment Research and Development Center (USAMERDC) has developed a computer program for use in assessing the effectiveness of a track width mine clearing plow moving through an area containing mixed mine types/fuze mechanisms. This program includes important modifications and extensions of some of the methods currently used for obtaining countermeasure-minefield effectiveness criteria and yields statistical information that cannot be determined from other existing models.

The approach to this problem makes use of a Monte Carlo computer simulation technique developed at the USAMERDC. Because of a need to investigate current and future threats for ascertaining mine-target interactions within a minefield, the computer program has been written in such a way that the only additional coding required is the so-called threat subroutine, against which the countermeasure effectiveness of the target can be determined.

INTRODUCTION

For some time, the Mine Neutralization Division (1-3)[1] of the Countermine/Counter Intrusion Department, USAMERDC, has been involved with analyses for determining probable mine clearing capability and blast vulnerability of a U.S. designed track width mine clearing plow from field test data. The long-range objective is to use these and other data to adequately define the capabilities and vulnerabilities of Soviet and Warsaw pact countermine equipment which may be deployed against U.S. inventory and developmental mines and mine systems. A preliminary objective is to provide data from these tests for use in a computer program in which target-threat interactions as a function of minefield density, pattern, and mine/fuze mixes can be simulated.

Information developed under this project will be part of the Air Scatterable Mine Program (4), the Countermine Development Program (5), and the Mine Development Program (6). Our participation in these programs is in an area of primary concern to the CM/CI Dept - to provide the best possible

[1] Underlined numbers in parenthesis refer to items in the list of references.

data which will contribute toward planning and coordinating future development, design, and/or modification of mines/mine systems/countermine hardware equipment.

This report describes a computer program for use in arriving at these objectives and includes important modifications and extensions of existing minefield models in use (7-9) for obtaining countermeasure-minefield effectiveness criteria.

Program COMMES (COunterMine Minefield Effectiveness Simulation) is written in Fortran IV for a Control Data Corporation (CDC)[2] 6600 Computer. Because of a need to investigate Soviet countermine equipment when deployed against various threats, COMMES was written in such a way that the only additional coding required is the so-called threat subroutine. This subroutine defines the location of all mines which must be specified by the user. Dimension statements limit the number of mines per row to 150, the number of rows of mines to 20, the number of targets per column to 25, the number of mine/fuze mixes to 2, and the number of targets on line to 5.

Program COMMES simulates the tank mounted mine clearing plow system as five separate and distinct types of areas and assesses their mine interaction kill probabilities. The model also considers target breach paths as a function of angular approach to the minefield, allows for exercising a so-called maneuver tactic (in the event that lead element of convoy becomes incapacitated and is a deterrent to remainder of column). In addition, a cost-effectiveness summary and an error analysis of calculated quantities of interest are included.

MODEL DESCRIPTION

General

This model was designed for use in arriving at probable effectiveness criteria for a U.S. designed track width mine clearing plow when deployed against various mines and mine systems and uses Monte Carlo techniques for doing this. The model basically consists of four functions or parts, the first of which deals with calculating mid-point locations of all mines in accordance with patterns and percentage mine/fuze mixes specified by the user. Having established the threat, the second function establishes initial positions for all targets attempting to breach the minefield. The third part addresses the dynamic interaction of a specific target against each mine within the boundaries of its lane, while the fourth function determines the result of each target-mine encounter. Figure 1 is a block diagram of the model and shows these basic functions.

Method Used in Determining Mine Positions

The mid-point positions of the mines are initially located within a rectangular area in accordance with the following quantities stipulated by

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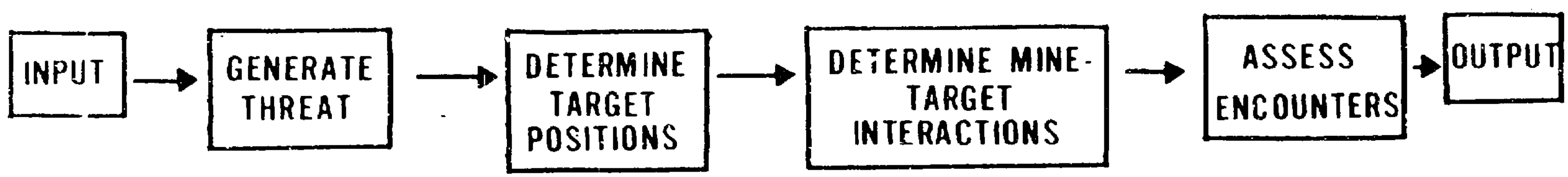
[2]Reference to specific manufacturer or product names is made for identification only and does not imply endorsement by the USAMERDC.

BLOCK DIAGRAM OF
COUNTERMINE MINEFIELD EFFECTIVENESS
SIMULATION MODEL
(COMMES)



the user: the depth and width of the minefield; the distance between mines in a row measured in the direction of the front; the distance between any two successive rows measured in the direction of the minefield depth; the initial coordinates of the left-most mine in a row relative to the center-line of the field; the number of rows of mines; the number of mines per row; the percent of total mines of type 2; and the angle THETA through which the minefield is rotated. Initially, all mine positions are expressed in terms of the center of the rectangular area noted above.

As it is of interest to consider target breach paths other than the strictly normal approach to the front (i.e., THETA = 0°), a coordinate translation on the initial threat itself is performed. Once these new mine coordinates are established, a random number generator routine is selected (using the Control Data Corporation library function RANF) and used for type classifying the individual mines.

Method Use in Determining Target Positions

The initial breach path for the left-most column is assumed to be equally likely to occur at any point across the front, subject to the condition that

$$CW \leq WMF, \tag{1}$$

where CW, the total width of the breaching column(s), is given by

$$CW = n(DX + BW + 2(WMB + GAP + SKID)) - DX, \tag{2}$$

when n defines the number of columns; DX is a constant distance between columns across WMF; and BW, WMB, SKID, and GAP define the width of the belly, moldboard, skid shoe, and gap between WMB and SKID, respectively. All of the quantities appearing on the right-hand side of equation 2 are specified in the input data.

The expression

$$X(I) = -WMF/2 + R\ (WMF - CW), \tag{3}$$

for i = 1,..., m for the m iterations, defines the initial random starting point for the left most edge of column 1, where R is a random number. All other column paths can then be established according to DX and the target parameters WMB, GAP, SKID and BW.

Method Used in Determining Mine-Target Interactions

The vehicular mounted plow assembly was simulated as three separately identifiable sections - the mold board, the skid shoe, and the gap between these two sections - as there is some evidence (1-3) that these areas exhibit significantly different probabilities of mine detonation and section kill given a detonation.

The following relation

$$X(J,K+1) \geq (XM(N,LL) - O.D./2) \text{ .AND. } X(J,K) \leq (XM(N,LL) + O.D./2) \qquad (4)$$

establishes a mine-target encounter, where: X(J,K) defines a coordinate for a particular section of our system; J refers to the target element; XM(N,LL) defines the mid-point of mine number N, type LL = 1 or 2; and O.D. is the diameter of this mine.

Method Used in Assessing Results of Mine-Target Encounters

The outcome of each mine-target encounter is determined in the following manner:

1. A random number, say URN1, is selected and compared to the value of PDET, the probability that this mine will have been detected by some means or other. If this random number is less than or equal to PDET, the mine is considered as having been negated. This mine, in effect, is removed from the field and the breach is continued.

2. If URN1 > PDET, it means that the mine was not detected. It could, therefore, detonate provided certain boundary conditions are satisfied and the mine itself is not a dud.

3. Boundary conditions are set up for each of the five sections being addressed. These constraints are established through the relation

TEST = BCØN(KK) * DIAMØFM(LL)/100,

where BCØN(KK) defines a percentage of the surface area of mine type LL that must be in contact with the target and DIAMØFM(LL) is the diameter of this same mine. If it is found that a section falls within these "free-zones", the mine is effectively removed from the minefield and the breach effort continued. Otherwise, we proceed to step 4.

4. A new random number is drawn and compared to the dud probability. If URN ≤ PDUD, the mine is a dud, removed from the threat, and all targets continue with the breach. If URN > PDUD, the mine has detonated which leads us to part 5.

5. Another random number is selected and compared to the probability of section kill, which is dependent on the frontal area of the system across which the interaction occurred. If this random number is greater than the kill probability value, then appropriate modifications to this system's configuration are made. In other words

   a. if a mine has detonated across the frontal assembly of the plow, exclusive of the moldboards, our system is degraded to look like the vehicle on which it's mounted.

b. if a mine detonated across the moldboards of the plow assembly, then the system is degraded to look like half a tank on one side, with the remainder having the appearance of the original system.

c. if a mine detonates across the belly portion of the system, this target is considered to be incapacitated (i.e., a mobile kill). This system is removed from the field, a decision is made regarding maneuvering around it, and all remaining systems continue with the breach.

If the random number drawn is greater than the kill probability value, we remove the mine from the threat and proceed with our mission.

The above procedures are continued until all targets have been incapacitated and/or until all targets have traversed the minefield. All target breach paths are then redefined and the program loops again. After a predetermined number of iterations, the following output is generated and, subject to a program control parameter, may be printed:

1. Coordinates for each mine as a function of mine number and type.

2. Coordinates for targets as they traverse field and a history of all mine-system interactions.

3. A history of each element's expectation of encountering a mine in the field.

4. Average frequency of 0, 1, 2,... encounters, incapacitations, detections, and duds expressed in terms of the five sections of the system assembly.

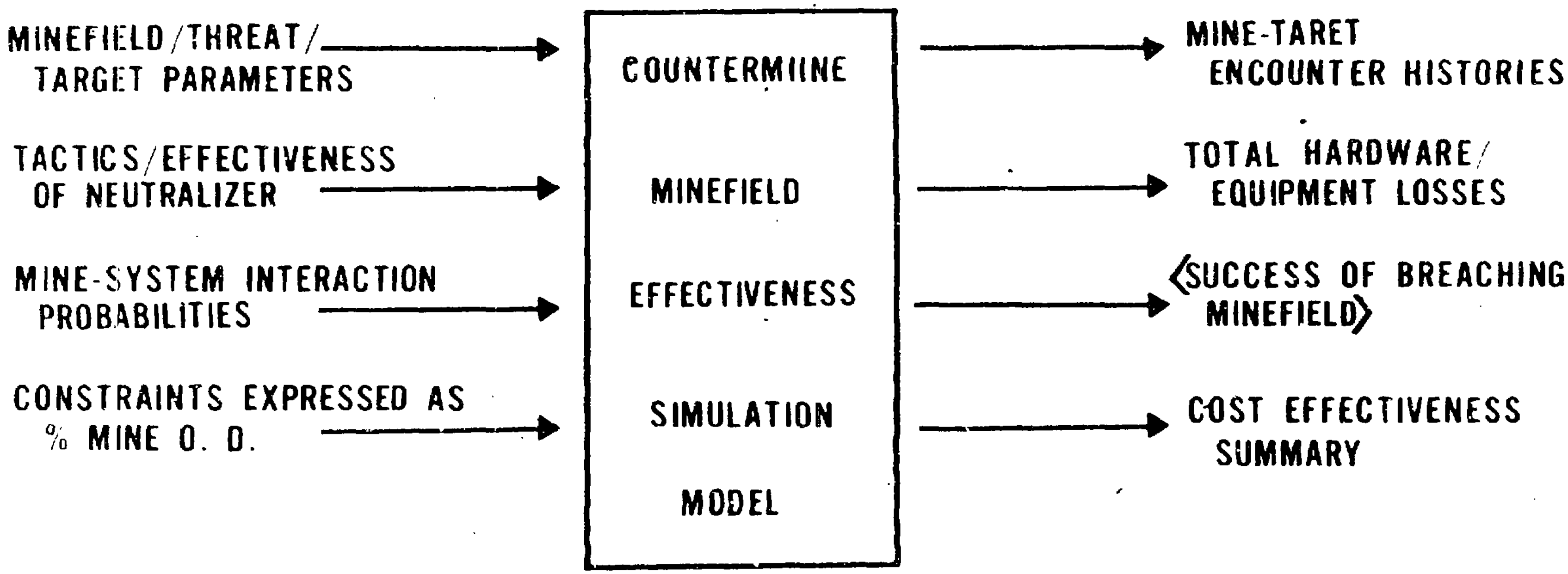
5. Expected encounter, dud, detection, and kill values for each target along with the uncertainty of these values.

6. A summary of the expected number of plow kills, vehicle mobility kills, and total kills as a function of various minefield densities/mine mix compositions.

7. A cost effectiveness analysis as a function of various minefield densities/mine mix compositions.

A modular representation of basic input/output information of program COMMES is shown in Figure 2. An example problem for which mine-target encounter histories, total hardware/equipment losses, and expected success of breaching a minefield is illustrated in Figure 3. These are some of the quantities useful in arriving at countermeasure-minefield effectiveness

COUNTERMINE MINEFIELD EFFECTIVENESS SIMULATION MODEL



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SIMULATION OF M-60 MOUNTED MINE CLEARING PLOW

TYPE FIELD STANDARD SOVIET MINEFIELD OF DENSITY = 2000 MINES/KM
TYPE MINES PRESSURE, M-15, 13 INCH O.D., 7.5 INCH PRESSURE PLATE
TILT ROD, M-21, 10 INCH O.D.
PERCENTAGE MINE MIX COMPOSITION(M-15/M-21) 90/ 10
TACTIC STRAIGHT BREACH
BREACH ANGLE IS NORMAL TO FRONT
CONSTRAINT(S) MOLDBOARD, 96.0 PERCENT OF M-15 MINES CAST ASIDE
4.0 PERCENT CONTACT TRACK AND DETONATE
SKID SHOE, 25.0 PERCENT COVERAGE OF PRESSURE PLATE FOR A DETONATION
NUMBER OF ITERATIONS = 500

MINE-TARGET INTERACTION PROBABILITIES

SECTION	PROB. OF DETECTION M-15	PROB. OF DETECTION M-21	PROB. OF DUD M-15	PROB. OF DUD M-21	PROB. OF KILL M-15	PROB. OF KILL M-21	DIMENSIONS INCHES
MOLDBOARD	0.0000	0.0000	0.0000	0.0000	0.0000	.6500	44.0
GAP	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	3.0
SKID SHOE	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	9.0
BELLY	0.0000	0.0000	0.0000	0.0000	0.0200	.1000*	88.0
TRACK	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	28.0

* BASED ON A CHAIN ATTACHED TO SKID SHOES TO CAUSE EARLY DETONATION AHEAD OF VEHICLE. IF OUR SYSTEM IS DEGRADED TO AN M-60, THIS VALUE BECOMES 1.0000.

E X P E C T E D   V A L U E S

VEH/COL		SYSTEM/MINE ENCOUNTERS ME	GAP	SKID	TRACK	BELLY	NUMBER OF DETECTS	NUMBER OF DUDS	PLOW KILLS MB	GAP	SKID	M-60 KILLS TRACK	BELLY	PROB. OF BREACH SUCCESS
1	1	5.3823	.4200	.6540	.6420	2.535	0.0000	0.0000	.1640	.0120	.3280	.6420	.0120	.3460
2	1	2.4235	.1340	.2080	.2250	.792	0.0000	0.0000	.0780	.1120	.1660	.2240	.0080	.7680
3	1	.5326	.0140	.0460	.0500	.164	0.0000	0.0000	.0260	0.0000	.0240	.0510	.0020	.9460
4	1	.0580	.0020	.0020	.0040	.012	0.0000	0.0000	0.0000	0.0000	.0020	.0040	0.0000	.9960
5	1	.0122	.0020	.0020	0.0000	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
6	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
7	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
8	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
9	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
10	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
11	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
12	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
13	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
14	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
15	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
16	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
17	1	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
18	1	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
19	1	0.0000	0.0000	0.0000	0.0000	1.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
20	1	0.0000	0.0000	0.0000	0.0000	1.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
[illegible]		[illegible]	.5720	.9260	.9220	3.316	0.0000	0.0000	.2680	.1240	.4600	.9210	.0220	
[illegible]		.0550	.0141	[illegible]	.0134	.0376	0.0000	0.0000	.0235	.0069	.0279	.0332	.0066	

criteria for the M-60/TWMP system.

Figure 4 is a cost effectiveness summary for this same system expressed as a function of various minefield densities/mine-mix compositions.

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SIMULATION OF M-60 MOUNTED MINE CLEARING PLOW

TYPE FIELD - STANDARD SOVIET MINEFIELD INSTALLED WITH A PMR-2 MINE LAYER
TYPE MINES   PRESSURE, M-15, 13 INCH O.D.,7.5 INCH PRESSURE PLATE
TILT ROD, M-21, 10 INCH O.D.
PERCENTAGE MINE MIX COMPOSITION(M-15/M-21)   0/100
TACTIC   STRAIGHT BREACH
BREACH ANGLE IS NORMAL TO FRONT
CONSTRAINT(S) MOLDBOARD, 96.0 PERCENT OF M-15 MINES CAST ASIDE
4.0 PERCENT CONTACT TRACK AND DETONATE
SKID SHOE, 25.0 PERCENT COVERAGE OF PRESSURE PLATE FOR A DETONATION
NUMBER OF ITERATIONS = 500

MINE-TARGET INTERACTION PROBABILITIES

SECTION	PROB. OF DETECTION M-15	PROB. OF DETECTION M-21	PROB. OF DUD M-15	PROB. OF DUD M-21	PROB. OF KILL M-15	PROB. OF KILL M-21	DIMENSIONS INCHES
MOLDBOARD	0.0000	[illegible]	0.0000	0.0000	0.0000	.6500	44.0
GAP	0.0000	[illegible]	0.0000	0.0000	0.0000	1.0000	3.0
SKID SHOE	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	9.0
BELLY	[illegible]	[illegible]	0.0000	0.0000	0.0000	.1000*	85.0
TRACK	[illegible]	[illegible]	[illegible]	[illegible]	1.0000	1.0000	28.0

* BASED ON A CHAIN ATTACHED TO SKID SHOES TO CAUSE EARLY DETONATION AHEAD OF VEHICLE.
IF OUR SYSTEM IS DEGRADED TO AN M-60, THIS VALUE BECOMES 1.0000.

------------- E X P E C T E D B R E A C H C O S T (T H O U S A N D S O F D O L L A R S) -------------

DENSITY MINES/M	100/0	90/10	80/20	70/30	60/40	50/50	40/60	30/70	20/80	10/90	0/100
	PERCENTAGE MINE MIX COMPOSITION(M-15/M-21)										
.5	41.726	54.127	56.237	82.495	103.530	104.141	122.203	129.967	142.324	151.124	189.781
1.0	96.661	119.043	134.550	164.977	186.107	218.553	227.839	255.190	272.169	360.552	427.270
1.5	131.356	181.865	209.715	255.589	297.367	332.884	364.839	396.828	409.662	434.947	614.790
2.0	184.409	242.546	307.081	376.126	410.159	471.445	516.310	554.923	595.597	612.611	863.041
2.5	225.617	337.921	393.100	479.667	543.565	610.515	648.110	720.230	755.292	826.365	1073.719
3.0	301.338	362.249	433.916	556.813	626.767	729.438	744.479	824.321	867.082	889.761	1311.672
3.5	334.304	463.612	536.765	657.343	771.818	843.297	927.295	933.600	1035.434	1061.781	1502.268
4.0	374.995	506.883	657.859	759.860	895.313	952.301	980.331	1075.143	1146.748	1221.469	1735.093

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MIXED MINEFIELD MODELING

by

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The purpose of this paper is to present methodology to assess the effectiveness of Anti-Materiel (AM) minefield composed of a mixture of different types of AM fuzed mines. In particular, the family of scatterable mines is of main concern. In order to minimize countermeasures and obtain an effective minefield it is necessary to develop mines with specialized functions and seed the minefield with an appropriate mixture, each type to perform its particular task. The following two questions are resolved: (1) What should be the optimum fuze mixture, (2) How sensitive is the optimum mixture to minefield parameters?

To accomplish this task, the paper is partitioned into two parts: Part I - A Minefield Plow Effectiveness Model, Part II - Optimum Anti-Materiel Minefield Fuzing. The first part is concerned with a model for assessing the effects of mine clearing plows. The second part employs the results of the first part and obatins the optimum fuze mixture in the presence of several possible enemy countermeasure strategies.

The effectiveness criteria employed is to minimize the target survival probability. Though a number of other effectiveness criteria can be readily defined, it is necessary that the minefield be credible - that is, it must present a significant threat to a target attempting a breach. Hence chosing the mixture that maximizes the target kill probability appears to be a reasonable approach.

The approach taken is to introduce a suitable collection of system states in order to represent the interaction between the components of the target array as a Markov provess. Solution of the resulting coupled system of first order linear differential equations gives rise to survival probabilities for the target components as a function of the minefield parameters.

PART I - A MINEFIELD PLOW EFFECTIVENESS MODEL

INTRODUCTION

The purpose of this section is to present a model for analyzing the effectiveness of mine clearing plows mounted in front of the tracks of a tank in a AM minefield. The plow's function is to sweep AM mines away from the path of the tank's tracks thereby preventing a track - AM mine contact, thus increasing the tank's survivability.

The minefield to be considered consists of a mixture of AM munitions with three different types of fuzes; anti-handling (AH), pressure (PR), long impulse (LI). AH munitions will almost certainly be detonated upon contact with the plow whereas PR and LI munitions will usually be pushed aside without detonation. A major purpose of employing AH munitions in the minefield is to countermeasure plows.

DEFINITIONS AND ASSUMPTIONS

The following definitions and assumptions are employed by the model:

1. The model considers a single tank with separate plows mounted in front of each track. The plows can be raised and lowered as required independently of each other. For example, if the left plow should become unusable, it can be raised. The tank can then proceed through the minefield using the right plow to clear mines from the path of the right track but with the left track vulnerable. If both plows should become damaged, they can both be raised, and the tank can then proceed without any plowing capability.

2. The plow can be envisioned as consisting of two parts: the moldboard and skidshoe The mold board is used to do the plowing while the skidshoe is used to maintain the proper relationship between the moldboard and the ground.

Let: KMB denote the effective width of the moldboard
KSH denote the effective width of the skidshoe

Thus: $KMB \cdot \Delta x$ = the area of the minefield contacted by the mold board when the tank plow assembly moves distant Δx through the minefield.

$KSH \cdot \Delta x$ = the area of the minefield contacted by the skidshoe when the tank plow assembly moves distance Δx through the minefield.

3. The munitions employed are only effective only against the tank tracks. We denote the effective width of each track by KT, thus

$KT \cdot \Delta x$ = the area of the minefield contacted by one of the tank tracks when the tank plow assembly moves distance Δx through the minefield.

4. The minefield consists of a mixture of three types of munitions: AH, PR, AND LI. We define the minefield parameters ρ , $\lambda 1$, $\lambda 2$.

Where:

ρ denotes the total minefield area density (mines/ft2)
$\lambda_1 \cdot \rho$ denotes the density of the AH mines (mines/ft2)
$\lambda_2 \cdot \rho$ denotes the density of PR (mines/ft2)
$(1-\lambda_1-\lambda_2)\rho$ denotes the density of LI mines (mines/ft2)

Note that λ_1, λ_2, ≤ 0, and $\lambda_1 + \lambda_2 \leq 1$

5a. When a plow contacts a mine we define the following mine detonation probabilities

Mine type	Probability of Detonation	
	Moldboard	**Skidshoe**
AH	PD1	PD2
PR	PD3	PD4
LI	PD5	PD6

Ideally, PD1 and PD2 = 1, PD5 and PD6 = 0

b. When a tank **track** contacts a mine we define the following mine detonation probabilities

Mine type	Probability of Detonation
AH	TD1
PR	TD2
LI	TD3

6a. When a mine detonates against a plow, we define the following plow kill probabilities

Mine Type	Probability of Plow Kill	
	Moldboard	**Skidshoe**
AH	PK1	PK2
PR	PK3	PK4
LI	PK5	PK6

b. When a mine detonates against a track, we define the following tank mobility kill probabilities

Mine Type	Probability of Tank Mobility Kill
AH	TK1
PR	TK1
LI	TK3

7. When a plow clears a mine, given that the mine does not detonate, there exists a small but non-zero probability that the mine can roll back into the path of the tank's track. We denote this probability for each munition as follows:

Mine Type	Roll Back Probability/No Detonation	
	Moldboard	**Skidshoe**
AH	PR1	PR2
PR	PR3	PR4
LI	PR5	PR6

DIFFERENTIAL KILL PROBABILITIES

With the preceeding definitions and nomenclature, we are now in a position to obtain expressions for the differential tank and plow kill probabilities when the tank moves from x to x + Δx.

1. Plow Kill

In order to determine the differential plow kill probability, we must consider the moldboard and skidshoe separately.

a. Moldboard

In order for a moldboard plow kill to occur, the mold board must contact a munition, the munition must detonate, and the detonation must inflict sufficient damage to the moldboard. One obtains considering all three munition types:

Prob (Moldboard plow kill in x to x + Δx)

$$= PK_1 PD_1 \lambda_1 \rho K_{MB} \Delta x + PK_3 PD_3 \lambda_2 \rho K_{MB} \Delta x + PK_5 PD_5 (1-\lambda_1-\lambda_2) \rho K_{MB} \Delta x$$

$$\triangleq \alpha_1 \rho \Delta x$$

b. Skidshoe

Similarily for a skidshoe plow kill to occur, the skid shoe must contact a munition, the munition must detonate, and the detonation must inflict sufficient damage on the skid shoe to render it inoperative. One obtains considering all three munition types:

Prob (skidshoe plow kill in x to x + Δx)

$$= PK_2 PD_2 \lambda_1 \rho K_{SH} \Delta x + PK_4 PD_4 \lambda_2 \rho K_{SH} \Delta x + PK_6 PD_6 (1-\lambda_1-\lambda_2) \rho K_{SH} \Delta x$$

$$\triangleq \alpha_2 \rho \Delta x$$

2. Tank Track Kill

In order to obtain expressions for the differential tank track kill probability we must consider separately the case where the plow is down and the plow is raised

a. plow is raised:

As done for calculating plow kill probability, when the

plow is raised the differential track kill probability is given as the product of the mine contact probability, the mine detonation probability, and the kill given detonation probability. Consider all three munition types one obtains:

$$\text{Prob (track kill in } x \text{ to } x + \Delta x/\text{plow raised)}$$
$$= TK_1TD_1\lambda_1\rho K_T\Delta x + TK_2TD_2\lambda_2\rho K_T\Delta x + TK_3TD_3(1-\lambda_1-\lambda_2)\rho K_T\Delta x$$
$$\triangleq \alpha_3\rho\Delta x$$

b. plow is lowered:

When the plow is lowered in order for a track kill to occur, the mine must contact the plow, not detonate, roll back into the path of the tank track, detonate on the track, and inflict sufficient damage to the tank track to cause a tank mobility kill. One obtains considering the skidshoe and skidshoe separately and all three munition types.

$$\text{Prob (track kill in } x \text{ to } x + \Delta x/\text{plow lowered)}$$
$$= TK_1TD_1PR_1(1-PD_1)\lambda_1\rho K_{MB}\Delta x + TK_2TD_2PR_3(1-PD_3)\lambda_2\rho K_{MB}\Delta x$$
$$+ TK_3TD_3PR_5(1-PD_5)(1-\lambda_1-\lambda_2)\rho K_{MB}\Delta x$$
$$+ TK_1TD_1PR_2(1-PD_2)\lambda_1\rho K_{SH}\Delta x + TK_2TD_2PR_4(1-PD_4)\lambda_2\rho K_{SH}\Delta x$$
$$+ TK_3TD_3PR_6(1-PD_6)(1-\lambda_1-\lambda_2)\rho K_{SH}\Delta x$$
$$= \alpha_4\rho\Delta x$$

It should be observed that K_T, the effective track width, did not enter into this expression. The effective track width is built into the roll-back probabilities.

SYSTEM STATES AND STATE TRANSITION DIAGRAM

The survival probability of the tank and the plow are coupled since as long as the plow is functional it offers protection for the tank tracks. One can represent this complete system by defining the following distinct system states

$$S_{ij} = (i,j)$$

where i denotes the number of functional plows, = 0, 1 or 2, and j = 0 or 1, depending on whether the tank has suffered a mobility kill or not. We therefore have the following states.

- $S_1 = (2,1)$: both plows are functional and the tank has not suffered a mobility kill
- $S_2 = (1,1)$: one of the plows are functional and the tank has not suffered a mobility kill
- $S_3 = (0,1)$: both plows have been damaged but the tank has not suffered a mobility kill
- $S_{4a} = (2,0)$: both plows are functional but the tank has suffered a mobility kill
- $S_{4b} = (1,0)$: one of the plows are functional and the tank has suffered a mobility kill
- $S_{4c} = (0,0)$: both plows have been damaged and the tank has suffered a mobility kill

States S_{4a}, S_{4b}, and S_{4c} represent the states for which a tank has suffered a mobility kill. Transitions between these states are of no relevance. Indeed, the tank cannot move and transitions cannot even occur. For most computational purposes they can be lumped into a collective state S_4, i.e.

$S_4 = S_{4a} \cup S_{4b} \cup S_{4c}$: the tank has suffered a mobility kill

Using the definition of the system states and the differential kill probabilities derived in the preceeding section one can construct the state transition diagram shown in Figure 1. By construction, the state transition diagram graphically portrays the differential probabilities of the system changing from one system state to another system state when the system moves from x to x + Δx.

SYSTEM DIFFERENTIAL EQUATION

From the state transition diagram, one immediately obtains the following set of coupled difference equations for the system states

$$\begin{bmatrix} P_{S1}(x+\Delta x) \\ P_{S2}(x+\Delta x) \\ P_{S3}(x+\Delta x) \\ P_{S4}(x+\Delta x) \end{bmatrix} = \begin{bmatrix} 1-2(\alpha_1+\alpha_2)\rho\Delta x - 2\alpha_4\rho\Delta x & 0 & 0 & 0 \\ 2(\alpha_1+\alpha_2)\rho\Delta x & 1-(\alpha_1+\alpha_2)\rho\Delta x - (\alpha_3+\alpha_4)\rho\Delta x & 0 & 0 \\ 0 & (\alpha_1+\alpha_2)\rho\Delta x & 1-2\alpha_3\rho\Delta x & 0 \\ 2\alpha_4\rho\Delta x & (\alpha_3+\alpha_4)\rho\Delta x & 2\alpha_3\rho\Delta x & 1 \end{bmatrix} \begin{bmatrix} P_{S1}(x) \\ P_{S2}(x) \\ P_{S3}(x) \\ P_{S4}(x) \end{bmatrix}$$

$$P_{S4a}(x+\Delta x) = P_{S1}(x)2\alpha_4\rho\Delta x + P_{S4a}(x)$$

$$P_{S4b}(x+\Delta x) = P_{S2}(x)(\alpha_3+\alpha_4)\rho\Delta x + P_{S4b}(x)$$

$$P_{S4c}(x+\Delta x) = P_{S3}(x)2\alpha_3\rho\Delta x + P_{S4c}(x)$$

Taking the limit as $\Delta x \to 0$, the following system of differential equations results:

$$\begin{bmatrix} P_{S1}'(x) \\ P_{S2}'(x) \\ P_{S3}'(x) \\ P_{S4}'(x) \end{bmatrix} = \begin{bmatrix} -2(\alpha_1+\alpha_2)\rho-2\alpha_4\rho & 0 & 0 & 0 \\ 2(\alpha_1+\alpha_2)\rho & -(\alpha_1+\alpha_2)\rho - (\alpha_3+\alpha_4)\rho & 0 & 0 \\ 0 & (\alpha_1+\alpha_2)\rho & -2\alpha_3\rho & 0 \\ 2\alpha_4\rho & (\alpha_3+\alpha_4)\rho & 2\alpha_3\rho & 0 \end{bmatrix} \begin{bmatrix} P_{S1}(x) \\ P_{S2}(x) \\ P_{S3}(x) \\ P_{S4}(x) \end{bmatrix}$$

$$P_{S4a}'(x) = 2\alpha_4\rho P_{S1}(x)$$

$$P_{S4b}'(x) = (\alpha_3+\alpha_4)\rho P_{S2}(x)$$

$$P_{S4c}'(x) = 2\alpha_3\rho P_{S3}(x)$$

SOLUTION TO THE SYSTEMS OF DIFFERENTIAL EQUATIONS

Solution to the preceeding system of differential equations can readily be obtained. One has for the system state probabilities provided $\alpha_3 \neq \alpha_1 + \alpha_2 + \alpha_4$

$$P_{S1}(x) = e^{-2(\alpha_1+\alpha_2+\alpha_4)\rho x}$$

$$P_{S2}(x) = \frac{2(\alpha_1+\alpha_2)}{\alpha_3-\alpha_1-\alpha_2-\alpha_4}\left[e^{-2(\alpha_1+\alpha_2+\alpha_4)\rho x} - e^{-(\alpha_1+\alpha_2+\alpha_3+\alpha_4)\rho x}\right]$$

$$P_{S3}(x) = \frac{(\alpha_1+\alpha_2)^2}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)^2} e^{-2\alpha_3\rho x} + \frac{(\alpha_1+\alpha_2)^2}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)^2} e^{-2(\alpha_1+\alpha_2+\alpha_4)\rho x}$$
$$- \frac{2(\alpha_1+\alpha_2)^2}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)^2} e^{-(\alpha_1+\alpha_2+\alpha_3+\alpha_4)\rho x}$$

$$P_{S4}(x) = \frac{\alpha_4}{\alpha_1+\alpha_2+\alpha_4}\left[1 - e^{-2(\alpha_1+\alpha_2+\alpha_4)\rho x}\right]$$

$$P_{S4b}(x) = \frac{(\alpha_1+\alpha_2)(\alpha_3+\alpha_4)}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)(\alpha_1+\alpha_2+\alpha_4)}\left[1 - e^{-2(\alpha_1+\alpha_2+\alpha_4)\rho x}\right]$$
$$- \frac{(\alpha_1+\alpha_2)(\alpha_3+\alpha_4)}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)(\alpha_1+\alpha_2+\alpha_3+\alpha_4)}\left[1 - e^{-(\alpha_1+\alpha_2+\alpha_3+\alpha_4)\rho x}\right]$$

$$P_{S4c}(x) = \frac{(\alpha_1+\alpha_2)^2}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)^2}\left[1 - e^{-2\alpha_3\rho x}\right]$$
$$+ \frac{(\alpha_1+\alpha_2)^2\alpha_3}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)(\alpha_1+\alpha_2+\alpha_4)}\left[1 - e^{-2(\alpha_1+\alpha_2+\alpha_4)\rho x}\right]$$
$$- \frac{(\alpha_1+\alpha_2)^2 4\alpha_3}{(\alpha_3-\alpha_1-\alpha_2-\alpha_4)^2(\alpha_1+\alpha_2+\alpha_3+\alpha_4)}\left[1 - e^{-(\alpha_1+\alpha_2+\alpha_3+\alpha_4)\rho x}\right]$$

$$P_{S4}(x) = 1 - P_{S1}(x) - P_{S2}(x) - P_{S3}(x) = P_{S4a}(x) + P_{S4b}(x) + P_{S4c}(x)$$

The survival probabilities for the plow and the tank are simply obtained by summing the appropriate state probabilities:

$$\text{Prob (Tank survives)} = P_{S1}(x) + P_{S2}(x) + P_{S3}(x)$$

$$\text{Prob (Tank and both plows survive)} = P_{S1}(x)$$

$$\text{Prob (Tank and at least one plow survives)} = P_{S1}(x) + P_{S2}(x)$$

In part II this model is applied to obtain a model for obtaining the optimum AM minefield fuzing mixture.

PART II - OPTIMUM ANTI-MATERIEL MINEFIELD FUZING

INTRODUCTION

The purpose of this section is to present an approach for determining the optimum fuzing mixture for AM minefields.

The function of employing different fuzes in a minefield is to minimize the effects of countermeasures employed by the enemy. In order to understand the advantages and limitations of the various mine types, one must examine the various strategies an enemy tank company commander can utilize. A partial list is given below.

1. No countermeasure
2. A plow can be mounted in front of each tank track to push mines aside.
3. A roller can be mounted in front of each track to roll over and thus detonate mines.
4. A line charge can be employed utilizing the shock wave it produces to detonate mines.

Let us now examine the effects of the different munitions against the tank under the countermeasure tactics listed above.

a. No countermeasure

If no countermeasures are employed the tank is of course vulnerable to all the mine types present in the minefield.

b. Plows are utilized

As long as the plows are functioning most of the PR and LI munitions will be harmlessly pushed aside. The AH mines will detonate against the plow. When a plow is destroyed the corresponding tank track becomes vulnerable to all mine types. Computation of the tank survival probability in this case requires the use of the Markov plow model developed in the previous section. Note that the AH mine type serves as a counter to plows.

c. Rollers are utilized

A roller placed in front of a tank track is a massive virtually indestructable object. The roller will harmlessly detonate practically all

AH and PR type munitions, and will initiate practically all LI munitions. The resulting tank mobility kill probability will depend upon its velocity and the length of the time delay incorporated in the long impulse mine: If the velocity of the tank is significantly slow or fast the mine will harmlessly detonate in front or behind the tank. Note that LI munitions serve as a counter to rollers.

d. A line charge is employed

A line charge will serve to modify the composition of minefield which the tank encounters. Most AH and some PR and LI munitions will be harmlessly detonated.

METHOD OF ANALYSIS

For each countermeasure the enemy employs one can calculate the tank survival probability as a function of the minefield parameters ρx, λ_1, and λ_2. Denote these survival probabilities as follows:

$P_1(\rho x,\lambda_1,\lambda_2)$: Tank survival probability without countermeasures

$P_2(\rho x,\lambda_1,\lambda_2)$: Tank survival probability when plows are employed

$P_3(\rho x,\lambda_1,\lambda_2)$: Tank survival probability when rollers are employed

$P_4(\rho x,\lambda_1,\lambda_2)$: Tank survival probability when a line charge is utilized.

Essentially, one has the situation where the enemy has available four strategies corresponding to all possible minefield mixtures. One approach to determine the optimum munition mix is to minimize a weighted average of the tank survival probabilities obtained when each countermeasure is employed separately. To this end, let

$$0 \leq b_1, b_2, b_3, b_4 \leq 1$$

$$\text{satisfying} \quad b_1 + b_2 + b_3 + b_4 = 1$$

Form the expression

$$W = b_1P_1(\rho x,\lambda_1,\lambda_2)+b_2P_2(\rho x,\lambda_1,\lambda_2)+b_3P_3(\rho x,\lambda_1,\lambda_2)+b_4P_4(\rho x,\lambda_1,\lambda_2)$$

and choose that mixture which minimizes this weighted sum expression. It should be noted that depending on the weights chosen emphasis can be placed on a particular countermeasure. For example if $b_1 = 1$, $b_2 = b_3 = b_4 = 0$, all emphasis is placed on the case where no countermeasures are utilized The mixture thus obtained would be optimum if one was certain no countermeasures would be used. It is necessary for the user to define an appropriate set of weights so that results obtained are meaningful to the problem under study.

REQUIRED INPUTS

Data input requirements are for the most part repeat of that required for the plow model in part b. Additional data is of course required to describe the cases of the roller and line charge.

REQUIRED FOR ROLLER MODEL

Detonation Probabilities

Against Roller:

Mine Type	Probability of Detonation
AH	DR_1
PR	DR_2
LI	DR_3

Against Tank Track:

Mine Type	Probability of Detonation
AH	TD_1
PR	TD_2
LI	TD_3

Tank Kill Probability/Detonation

Detonation on Roller

Mine Type	Probability of Tank Mobility Kill
AH	0
PR	0
LI	PLI (is velocity dependent)

Detonation on Tank Track

Mine Type	Probability of Tank Mobility Kill
AH	TK_1
PR	TK_2
LI	TK_3

Required for Line Charge Model

Detonation Probabilities

Mine Type	Prob mine is not detonated by line charge
AH	PRC_1
PR	PRC_2
LI	PRC_3

Fraction of minefield covered: FC (This represents the percentage of the minefield depth that can be cleared with a single line charge.)

EXPRESSIONS FOR THE TANK SURVIVAL PROBABILITY

We now give expressions for the tank survival probability in terms of the input parameters. We list both the differential kill probability and accumulated kill probability

1. No countermeasures

P(Tank mobility kill from x to x+Δx/Tank alive at x)

$$= 2K_T\Delta x\lambda_1\rho TD_1TK_1 + 2K_T\Delta x\lambda_2\rho TD_2TK_2 + 2K_T\Delta x(1-\lambda_1-\lambda_2)\rho TD_3TK_3$$

$$P_1(\rho x,\lambda_1,\lambda_2) = e^{-e_1\rho x}$$

where

$$e_1=2K_T\lambda_1TD_1TK_1+2K_T\lambda_2TD_2TK_2+2K_T(1-\lambda_1-\lambda_2)TD_3TK_3$$

2. Mine Clearing Plows are employed

Expressions for the tank survival probability $P_2(\rho x,\lambda_1,\lambda_2)$ are developed in Part I.

3. Rollers are employed

If rollers are employes as a countermeasure, a tank mobility kill in x to x+Δx can occur in one of two ways

i. A mine type may fail to detonate on the roller, detonate on the tank track and inflict a tank mobility kill

ii. A LI munition may be initiated by the roller, detonate on the tank track, and thereby cause a tank mobility kill.

One obtains for the differential tank mibility kill probability

P(Tank mobility kill from x to x +Δx/Tank alive at x)

$$\left.\begin{aligned} &= 2K_T\Delta x\lambda_1\rho(1-DR_1)TD_1TK_1\\ &\quad+ 2K_T\Delta x\lambda_2\rho(1-DR_2)TD_2TK_2\\ &\quad+ 2K_T\Delta x(1-\lambda_1-\lambda_2)\rho(1-DR_3)TD_3TK_3\end{aligned}\right\}\quad \text{way (i)}$$

$$\quad+ 2K_T\Delta x(1-\lambda_1-\lambda_2)\rho DR_3PLI \qquad \text{way (ii)}$$

Therefore

$$P_3(\rho x,\lambda_1,\lambda_2) = e^{-e_3\rho x}$$

where
$$e_3 = 2K_T(1-DR_1)\lambda_1TD_1TK_1 = 2K_T(1-DR_2)\lambda_2TD_2TK_2 + 2K_T(1-DR_3)(1-\lambda_1-\lambda_2)TD_3TK_3 + 2K_TDR_3(1-\lambda_1-\lambda_2)PLI$$

4. A line charge is used

i. When the entire minefield is covered:

The case where a line charge is employed is similar to no countermeasure case except that the minefield density and mixture is modified. The differential kill probability is given by

P(Tank mobility kill in x to x+Δx/Tank alive at x)

$$= 2K_T \Delta x \lambda_1 \rho PRC_1 TD_1 TK_1 + 2K_T \Delta x \lambda_2 \rho PRC_2 TD_2 TK_2$$
$$+ 2K_T \Delta x (1-\lambda_1-\lambda_2) \rho PRC_3 TD_3 TK_3$$

Therefore

$$P_4(\rho x, \lambda_1 \lambda_2) = e^{-e_4 \rho x}$$

where

$$e_4 = 2K_T \lambda_1 PRC_1 TD_1 TK_1 + 2K_T \lambda_2 PRC_2 TD_2 TK_2$$
$$+ 2K_T (1-\lambda_1-\lambda_2) PRC_3 TD_3 TK_3$$

ii. When a portion FC, of the minefield is covered by the line charge one has

$$P_4(\rho x, \lambda_1 \lambda_2) = e^{-e_4 FC \rho x} \cdot e^{-e_1 (1-FC) \rho x}$$

A NUMERICAL EXAMPLE

Let us conclude this section with the following numerical example.

Weights:

No countermeasure	$b_1 = 0.0$
plow	$b_2 = 0.5$
roller	$b_3 = 0.12$
line charge	b_4 0.38

Minefield density: 1.0 mines/ft
Fraction coverage of line charge: 0.5

The results are given in figures 2 and 3. Figure 2 is a contour plot giving equi-survivability contours as a function of minefield composition. Note from this figure that the tank survival probability for specified parameters is very insensitive to the mixture employed. For example, if one chooses a misture of 40% LI one would obtain a tank survival probability of .44 which differs from the optimum by only .0415 or about 10%. Figure 3

is a sensitivity plot depicting the dependence of the optimum fuzing mixture on the linear minefield density. The figure clearly demonstrates that the optimum mixture is a very sensitive function of the minefield density.

CONCLUSIONS

In conclusion, it should be noted that the Markov appraoch represents an elementary solution to a very important problem area in mine systems development. Hopefully, this represents only a beginning and that the analytical and engineering tools that comprise the body of knowledge referred to as Operations Research will yield numerous powerful analytical methods to aid in the solution of mine and other weapon system design and effectiveness problems.

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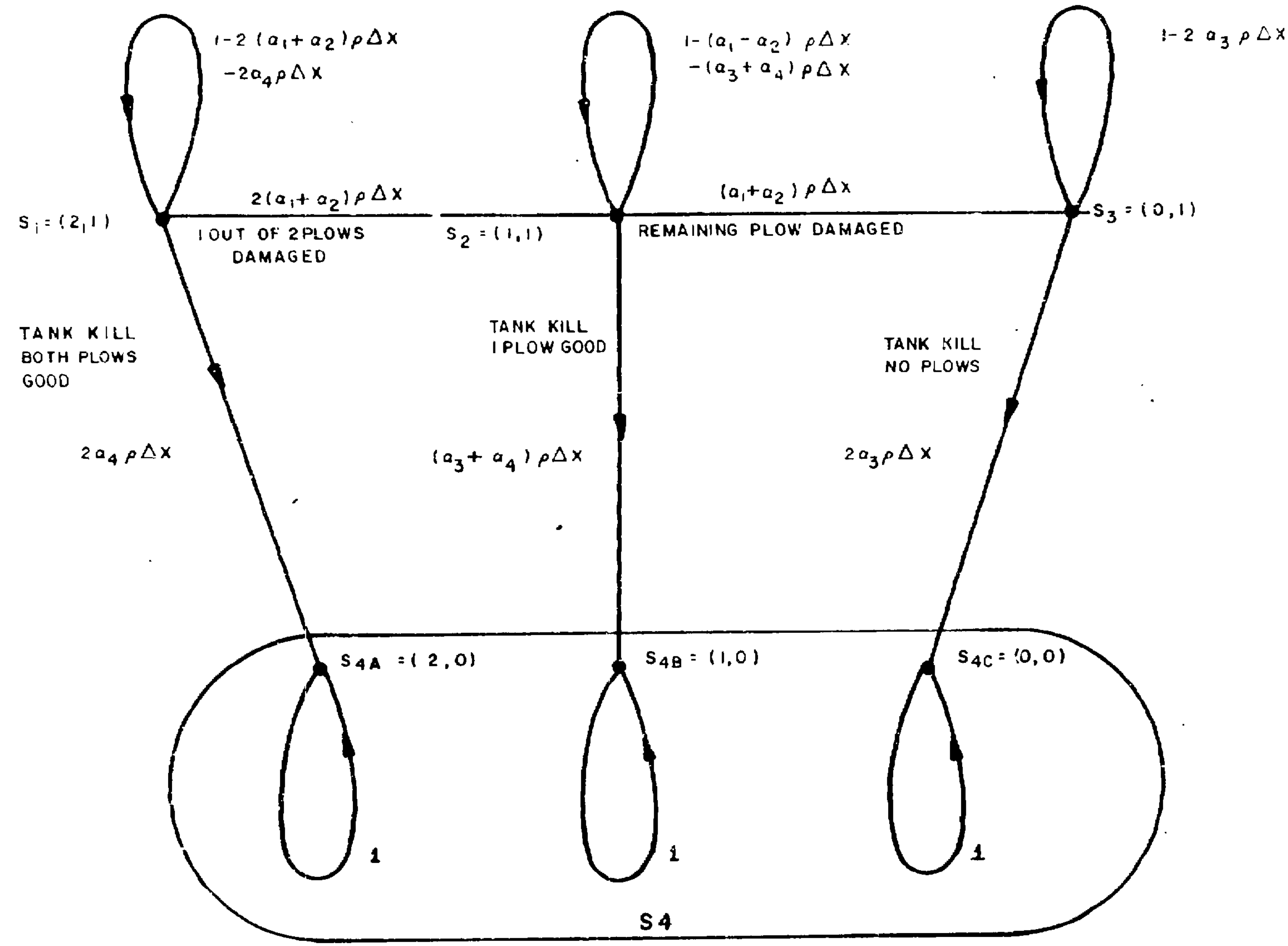


FIGURE 1. STATE TRANSITION DIAGRAM

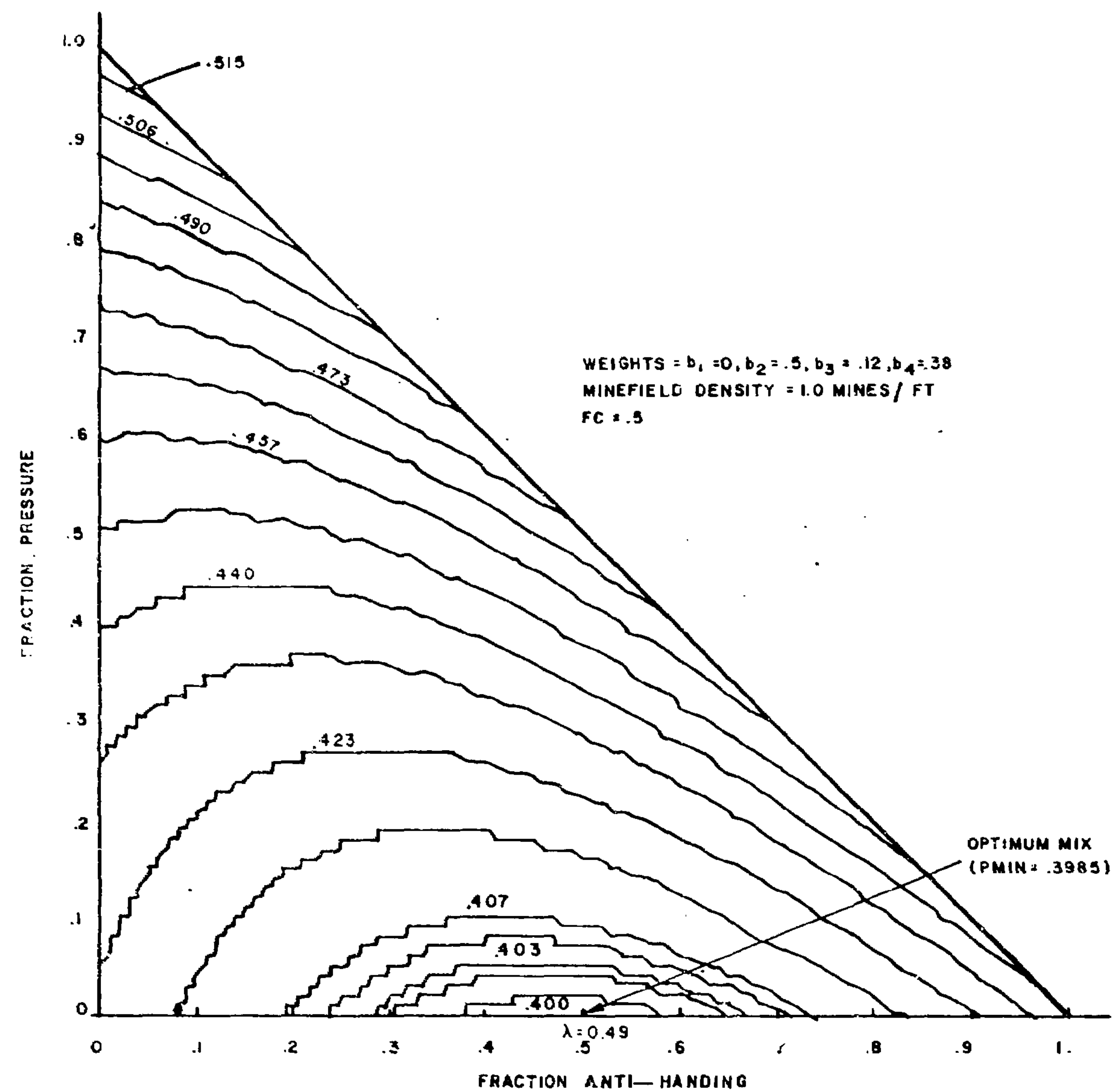


FIGURE 2 TANK SURVIVAL PROBABILITY CONTOURS

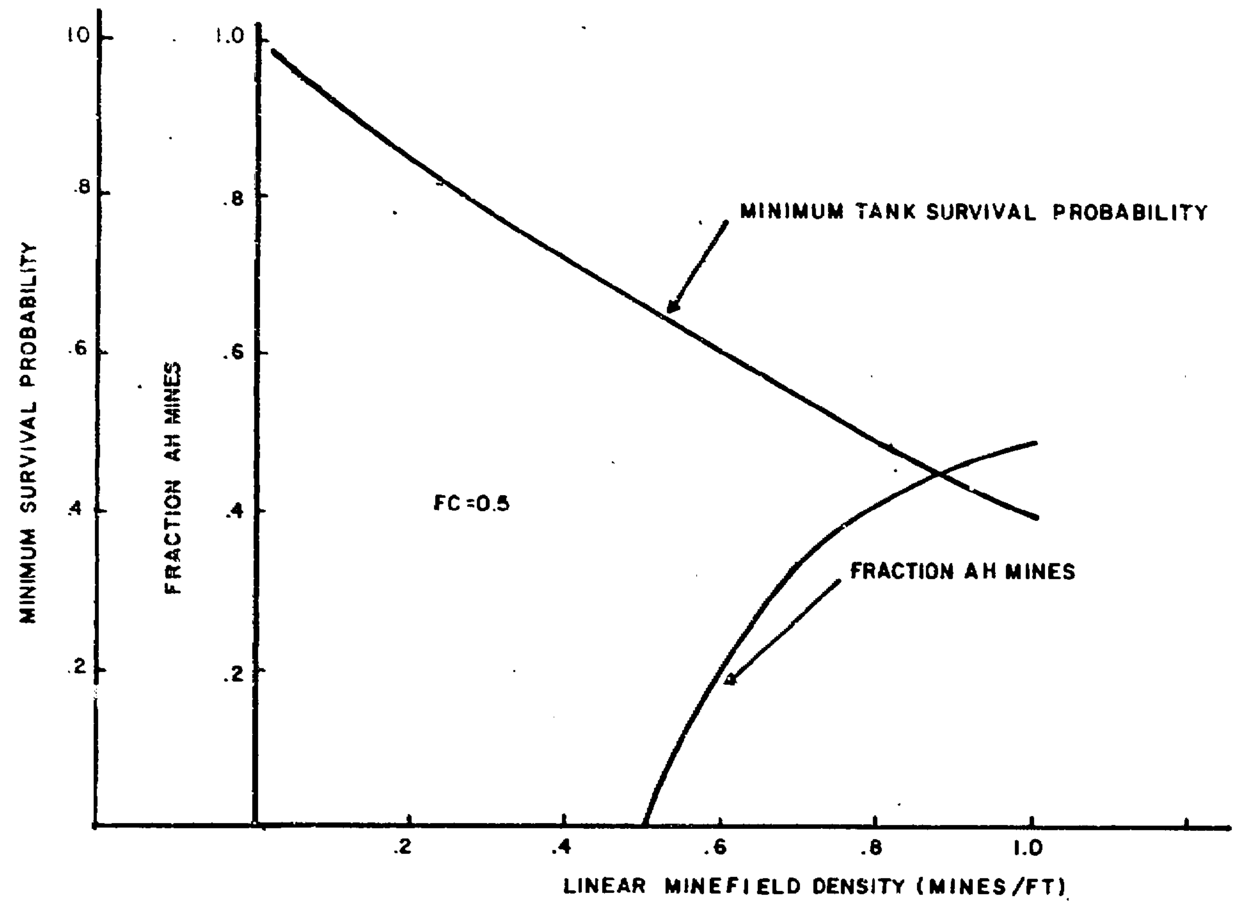


FIG. 3 DEPENDENCE OF OPTIMUM MIX ON MINEFIELD DENSITY

AD P000615

BATTLEFIELD RELATED EVALUATION AND ANALYSIS OF COUNTERMINE HARDWARE (BREACH)

Mr. Kenneth J. Dean and John A. Christians

USAMERDC

ABSTRACT

This paper presents the methodology being used at MERDC to describe and evaluate the effectiveness of the integrated family of countermine equipment. The scenarios and heirarchy of models used to determine systems effectiveness and operational feasibilities are described. The essential countermine missions of the Army are examined along with a comparative evaluation of a typical baseline system.

INTRODUCTION

Mechanized war and some of the problems it presents to the combat soldier in clearing mines is illustrated by the "Sad Sack" who was the pride of the Army as he led the advance of the armored column, in a cartoon which originally appeared in Stars and Stripes sometime during WW II. It is surprising at times how little some things change. In the intervening years, we have witnessed significant technological progress in such areas as mobility and firepower; yet, the man portable detector and its companion the probe, remain essentially the same. Its electronics are the best and lightest available to be sure; but the basic design principal of WW II that forces search operations to be conducted at a fraction of a normal walking pace is retained!

Vietnam focused attention on the difficulties of countermining and the heavy materiel losses that can be accured from the random/harrassment type threat encounter there. Low density threats proved more vexing to our forces relying on their mobility than conventional barrier minefield of WW II with their clearly defined and marked boundaries. Some have compared the countermine problem to that of finding a needle in a haystack. It is even worse than that, because most of the time the search has to be conducted from a platform moving at convoy speeds.

SYSTEMS VIEW

The seriousness of the mine threat posed for a central European conflict coupled with the operational experience of Vietnam, has placed renewed emphasis on the Countermine Program. A small but critical part of that

program is the systems effort charged with two basic objectives: to support R&D by conducting near term system trade-offs and defining mid to long term design goals; and to provide the field commander with a "How-to-do-it" book on countermining. The OR or SA approach to these objectives is diagramed in Figure 1: that is to define, gather data, model, evaluate, validate, plan for implementation, and make appropriate recommendations to decision makers. In summary, the Countermine Systems Effort is viewed as an extension of hardware research and development into the user's world and considers the effects of tactics, doctrine, and hardware in the total spectrum of countermine activity taking place on the battlefield.

A countermine system is not a single line item piece of hardware, nor a universal mine detector. A countermine system is a composite of appropriate capabilities. It must be the commander's decision as to whether time is critical, manpower is critical, performance critical, etc. He is the one who knows what the real-time threat is or may be, what the environment is or will be, what his mission is and what constraints are applied, what the importance of the mission is, and what his capabilities are at that point in time. You will notice that more than just hardware is included in capabilities - people, tactics, techniques may well be as important as hardware, or even more so, in successfully completing the mission. The characterizations of these various inputs are discussed in detail in the following paragraphs.

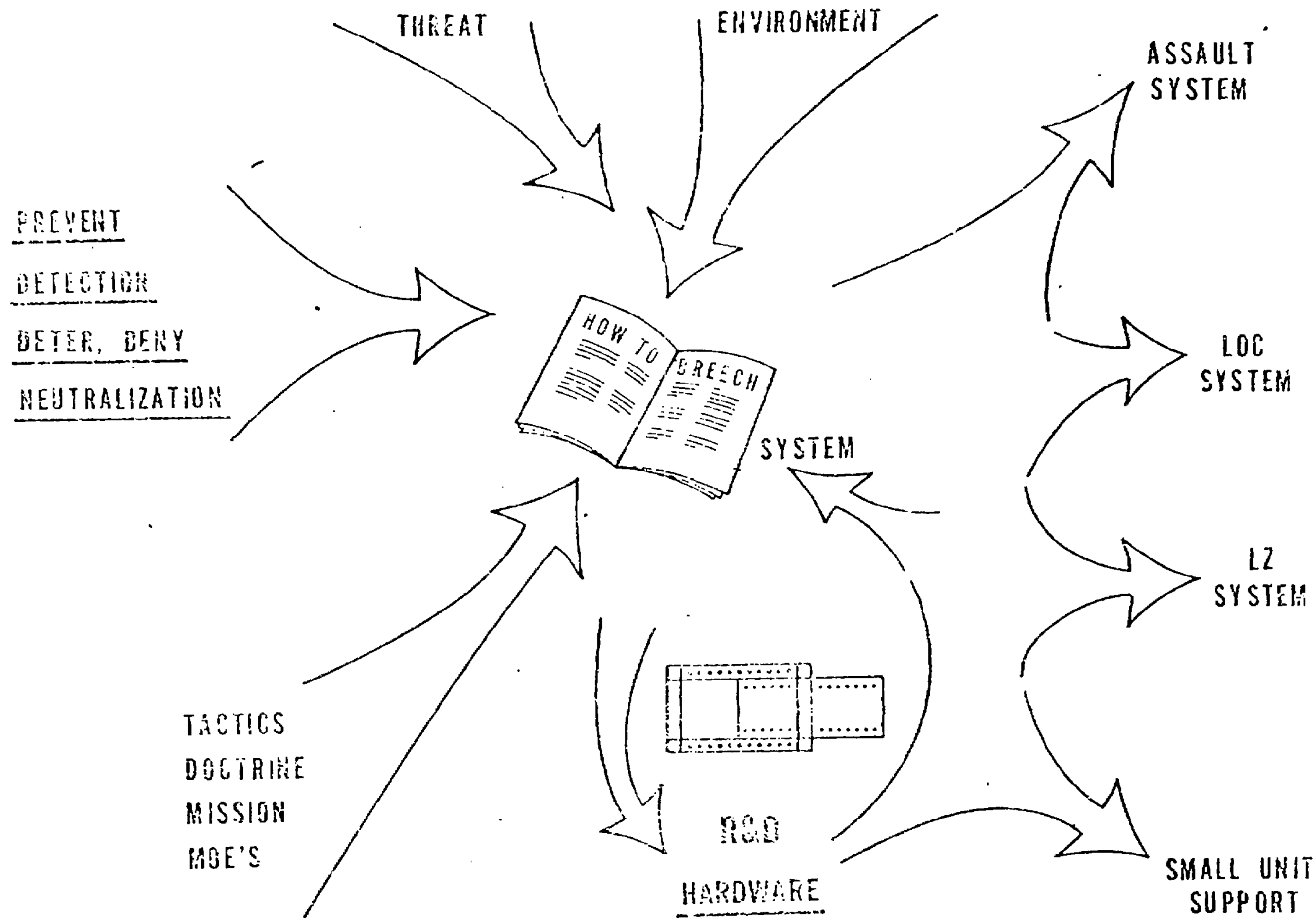
The environment is obviously critical, for it influences when missions start, how they are conducted, and how fast. It also influences countermining for the reasons above, and also in a technical or equipment performance sense. For example, infrared is very sensitive to atmospheric conditions, and to some extent terrestrial conditions. If it rains, the thing does not work. Additionally, if missions are planned to happen under conditions of low visibility (foggy, cloudy, etc), then the commander never need worry about whether he should use an IR device - the answer is no, the device simply wouldn't function.

The countermine system effort involves many organizations outside of MERDC. For example, we are being well supported and have the full participation of the user through the Training and Doctrine Command; the Navy and Marine Corps are actively participating in the areas of amphibious breach assaults and riverine Countermine Warfare. In the collection of the data base, so critical to systems analysis techniques, we have the active support of over nine separate organizations.

In the area of threat, we are concerned with the type of mine, type of fuze, emplacement, and patterns, as a function of missions. For example, patterned anti-tank and anti-personnel minefields are the threat for most armored or mechanized infantry assaults; random or simple pattern anti-tank and anti-personnel mines may be encountered in roads and railroad tracks; random anti-personnel mines or booby traps may be encountered along trails or in urban areas by Infantry troops.

Figure 1

COUNTERMINE SYSTEM



The major functions or approaches to countermining can be categorized as surveillance, prevention/area denial, detection, and neutralization. Hardware research and development efforts are primarily oriented towards detection, marking, and neutralization of mines while surveillance and area denial are normal Army activities which can have an important secondary role in countermining. In surveillance, for example, the countermine support may well make use of sensors, radars, night observation devices, and patrols with the express purpose of seeing the mine planter or sapper before he buries the mine. This intelligence can then have two follow up actions; deterrence/denial response or a reduction in the countermine effort because the approximate location of the buried mine is known. Other areas could also be considered in a dual role such as operations planning and assessment, for as previously mentioned it is the field commander who must design and implement specific countermine efforts. Mobility could also be included as a reminder that one of the important objectives of mining is to slow or delay the enemy. Therefore an important objective of countermining should be to help maintain mobility

The last and most complex area is the Tactics, Doctrine, etc. Obviously, it is a much more involved subject than can be treated here; however, the Training and Doctrine Command has assisted in the preparation of very detailed logic charts representing the tactics and doctrine of the field Army. The use of these charts will be illustrated later in describing the countermining simulation.

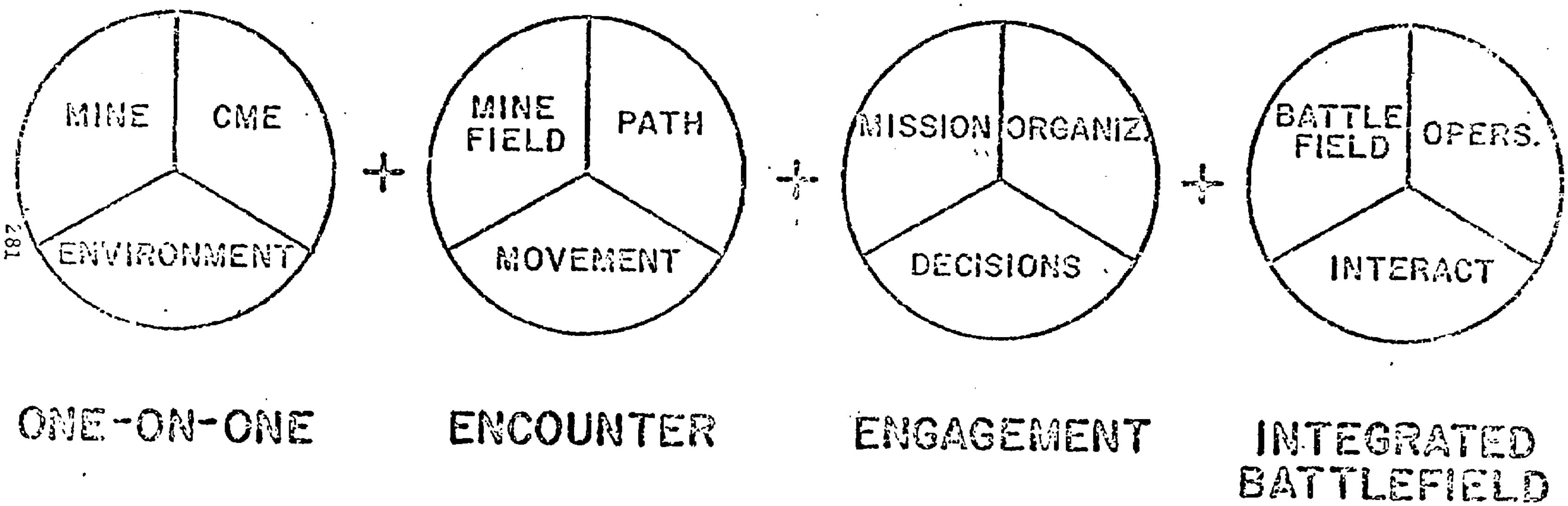
The operational parameters, threat, environment, tactics, etc., along with possible hardware mixes are sufficient to define the framework in which the countermine capability can be evaluated. Values for these input parameters plus their variations must be reasonably representative of real world conditions or the simulation will obviously be biased. Comparative analysis can reduce the risk involved to a certain extent but even here the variation of certain parameters can have a significant effect on results. To avoid these problems and still retain a reasonable number of situations, four mission categories were selected: Armor/Mechanized Assault; Line of Communication (LOC) Security; Infantry Assault; and Small Unit Operations. It is generally felt that these four missions are sufficiently varied in terms of threat, tactics, and terrain that most, if not all, countermine requirements can be realistically evaluated.

MODELS

To support the detailed analysis associated with the individual missions and equipment mixes, we have developed the hierarchy of models/simulations shown in Figure 2. The one-on-one implies an examination of the interaction of a specific device (detector, neutralizer, etc.) with a specific type of threat (metal AT mine).

Figure 2

BREACH MODELS



When multiple targets or mines are used and the device now has movement over a path, we define this as an encounter. This is essentially the level that specific hardware effectiveness is determined.

The engagement adds the mission, organization and decisions. This is equivalent to a mission without enemy. Much of the coordination with the user representatives has been at this level.

When an enemy is introduced, and he can shoot and destroy personnel and equipment, we then have the integrated battlefield.

Our in-house development of methodology stops at the engagement level. The countermine simulations at the two lower levels function in a batch mode, i.e., input data, replicate calculations many times, and calculate averages, means, etc. At the engagement level, we have in addition the capability to interactively work the problem and allow human decisions to be made and inputed on the spot, as is done in the real world. The outcome of that decision is then calculated by the simulation.

At the integrated battlefield level we will use an existing simulation called DYNTACS (Dynamic Tactical Simulator). Orginally developed by Ohio State to support tank design and development, it has been modified and expanded considerably to handle many combat conditions involving mobility, firepower, communications, and minefields. This model is presently being used by the Armament Command (formerly Weapons Command) to support the Family of Air Scatterable Mine Study (FASCAM); and by the Missile Command.

The one-on-one level consist of analytic/probabilistic models describing the performance of individual pieces of countermine hardware. The basic catergories such as minefields, detectors, vehicles, etc. are illustrated in Figure 3. In terms of the program software, these are data processing routines which load input data, characterizing the threat and hardware, into the appropriate tables. The one-on-one models are then combined and driven by appropriate executive commands to yield either encounter or engagement level exercises.

One of our initial one-on-one type models deals with the man portable mine detectors. The computer program walks a man down a path and swings the mine detector back and forth, as a function of forward speed and stride length of the individual. The model determines the distribution of offset distance between the path of the detector and the mine, and combines this with basic detector performance to produce signal output, in DB or frequency vs the percent of time that it will occur. If this is repeated for different stride lengths, a parametric relation results, showing the effect of slow vs rapid mine sweeping.

An example of the encounter type model is shown in Figure 4. This is a computer generated output of one trial firing of the SLUFAE mine neutralizer against a 300 meter field. 144 rounds were fired, which resulted in an 8 meter path with 2 live mines still present and 30 neutralized mines.

Figure 3

MODEL STRUCTURE

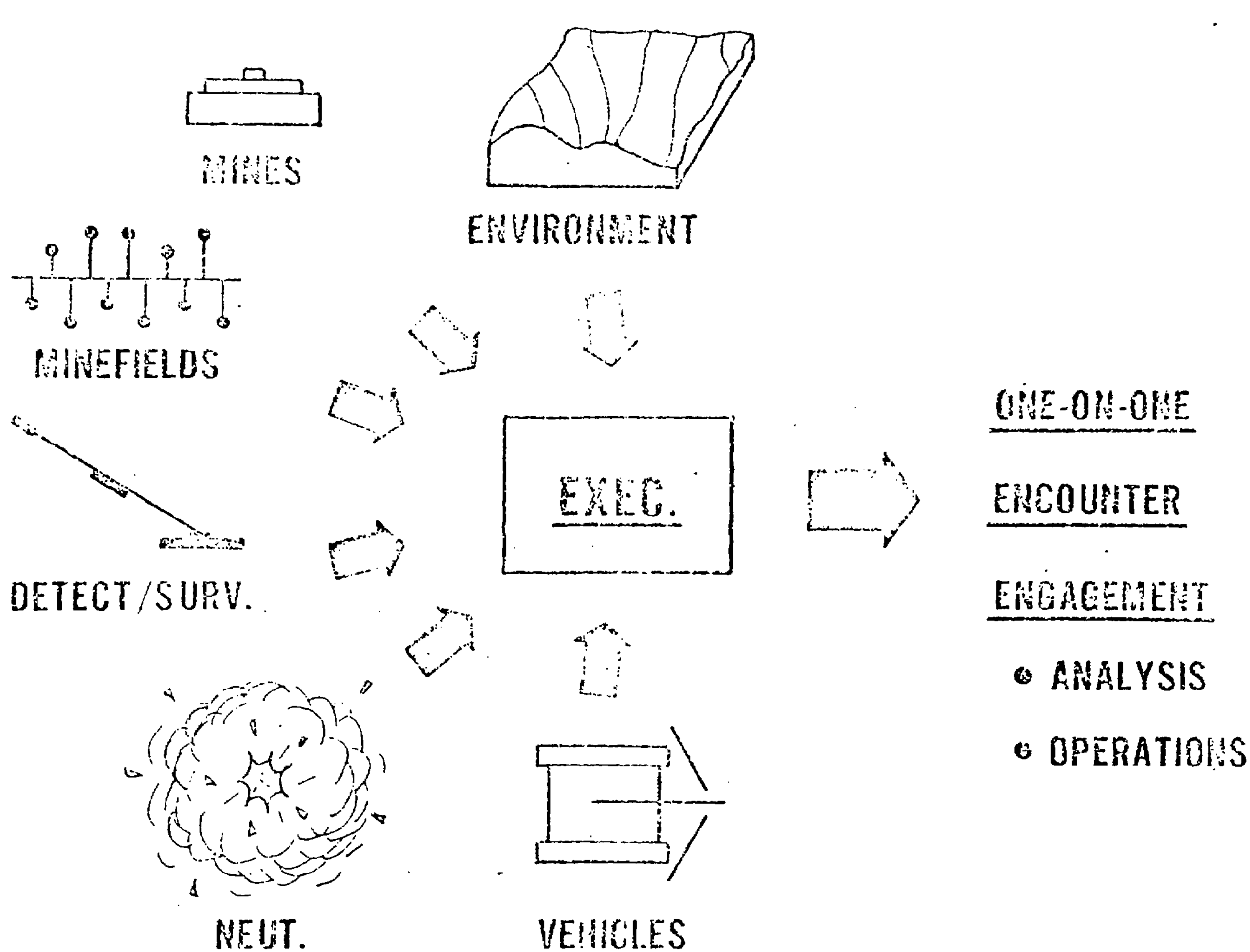
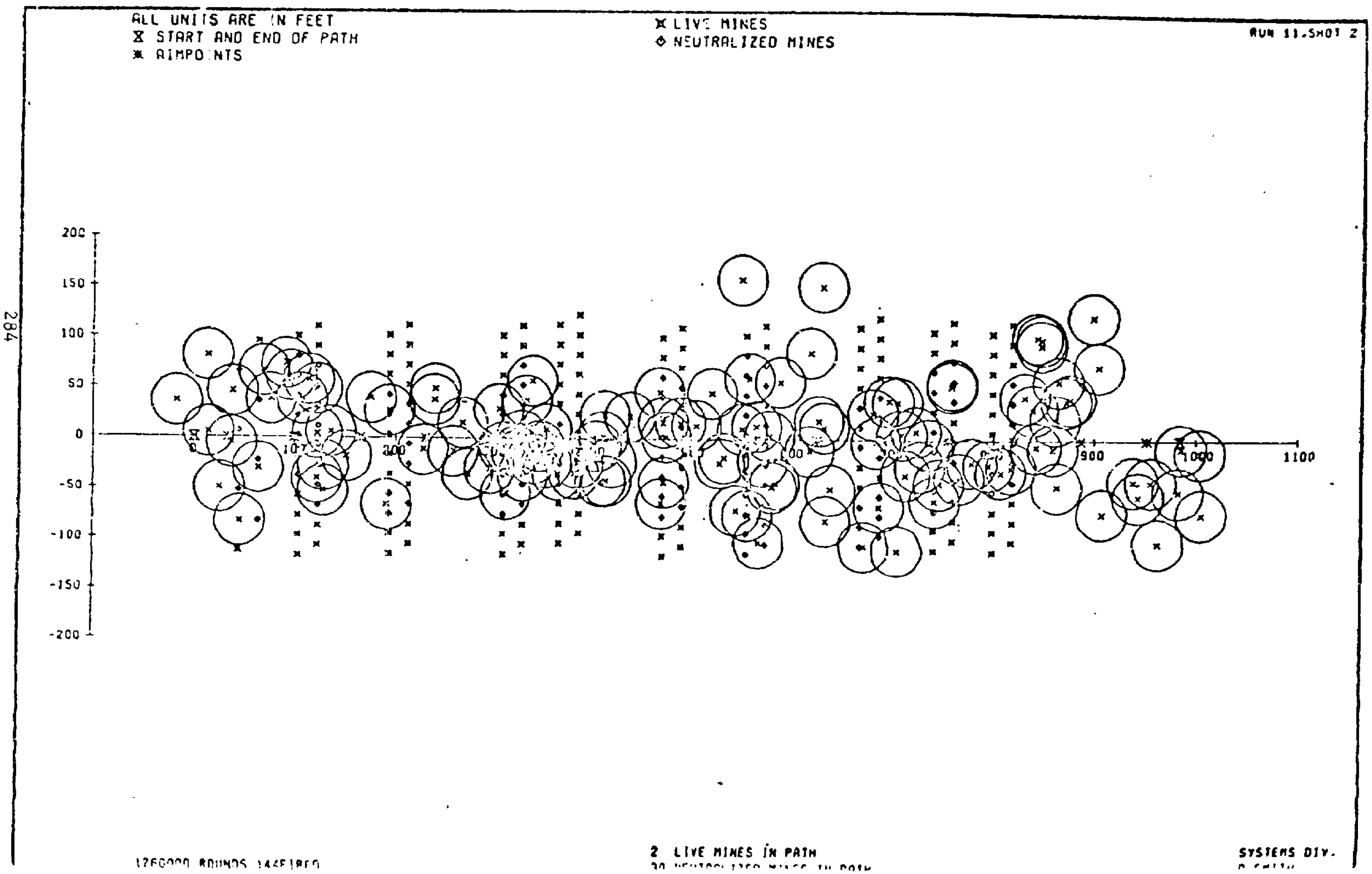


Figure 4



ALL UNITS ARE IN FEET
START AND END OF PATH
AIMPOINTS
LIVE MINES
NEUTRALIZED MINES
RUN 11.SHOT 2
200
150
100
50
0
-50
-100
-150
-200
900
1000
1100
2 LIVE MINES IN PATH
SYSTEMS DIV.

An example of an engagement can be illustrated by using the encounter model to develop the situation. First, the lead tank of an armored unit moving cross country, but not in enemy territory, encounters a mine and suffers a mobility kill. Secondly, the commander has to make a decision on the next course of action. Was it a random mine his lead tank encountered or is he in fact inside an unmarked minefield?

As previously discussed, this decision can either be done by the computer through an extensive set of logic statements, or it can be made by a "commander" sitting at a computer terminal. In this case, the "commander" decided to fly a surveillance aircraft over the area. Fifty-two mines were detected in the 100 meter field-of-view.

Thirdly, the commander decides on the method of breaching. In this case, he chose a deliberate breach, using dismounted personnel. The teams cleared an eight meter swath and neutralized 15 mines.

Next, the commander decided to traverse the "cleared path" with a mine roller. This resulted in 5 more AP mines being detonated.

Finally he drove an M-48 tank successfully through the field and on the basis of this assumed the minefield was safely breached.

Unlike the real world, we can now go back and ask the computer for the true status of breach path. Doing this, the computer shows the actual situation existing in the cleared path as 20 neutralized mines and 5 AP mines that have not been detect[ed] or neutralized. The commanders decision that the path is safe is partly in error since casualties can result if dismounted personnel attempt to cross the marked path.

LOC BASELINE SYSTEM

For a typical application of this methodology, lets go back and look at "Sad Sack's" problem of clearing an LOC with current man portable detectors. A comparative analysis at the encounter level should suffice for this situation.

The secenario is a 10km length of secondary road with a relatively high threat density of one anti-vehicular mine per kilometer. Mine sweeps are randomly conducted 20 times per month yielding a total length of 200km. Three operational constraints are applied to these sweeps:

a. Standard Sweep - units proceed at normal pace over entire LOC.

b. Restricted Sweep - units proceed at normal pace for a maximum of two hours.

c. Concentrated Sweep - units travel at road speeds (40 km/hr) to known areas of mining activity assumed to be concentrated in 10% of the LOC.

The restricted sweep simulates a situation where a convoy must proceed at a given time regardless of whether the sweep is completed. The 10% restricted case occurs when the operational tactics of the mine layers are well known through history or intelligence. The standard sweep is used for a comparative base.

The equipment mix for purposes of this example can be taken as the two standard metallic and non-metallic detectors (AN/PSS-11 and AN/PRS-7) plus a developmental thermal imaging device. The measures of effectiveness include the number of mines detected, the distance traveled, and the total sweep time, although primary emphasis is placed on the number detected.

For the standard sweep, the man portable detectors are the better items. A final selection between the two is dependent upon the nature of the threat. For a mixed threat containing both metallic and non-metallic mines, the preference goes to the PRS-7. In a time critical situation such as the restricted sweep, the search rate or speed of the thermal device offsets its lower detection rate making it the better device. If the search rate of the man portable detectors is augmented by rapid movement between areas of suspected mining activity, as is possible in the concentrated sweep, their performance again becomes superior.

From this simple analysis, it can be concluded that one of the critical parameters affecting performance is the operational search rate. A rather apparent observation that has previously been noted by several individuals; yet, this same parameter has limited road sweeps since WW II.

Operational data from Vietnam, a situation similiar to the time constrained

AD P000616

AVVAM-1 and Tank Vulnerability Sensitivity Studies

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Introduction

AVVAM-1 (Armored Vehicle Vulnerability Analysis Model - first version) is a conceptual model and associated digital computer code recently developed (1) at the Ballistic Research Laboratories to analytically assess the vulnerability of all types of combat vehicles to hostile conventional weapons. It is applicable to combat vehicles in general including tanks, armored personnel carriers, armored reconnaissance vehicles, etc. AVVAM-1 is another step in the continuing vulnerability methodology development which has been pursued at BRL since tank vulnerability work was initiated at the Laboratories in 1950.

Early effort in the 1950's took the form of an extensive test firing program. Guided by the results of these tests, a method to evaluate the terminal effects of antitank warheads against tanks evolved in the late 1950's. This work originated the "damage concentration" concept and showed that a relationship exists between armor distribution, projectile perforation characteristics, and component kill probability. A "kill" is defined in terms of functional loss with the types of "kill" classified as follows:

M Kill:	Loss of mobility
F Kill:	Loss of firepower
M or F Kill:	Loss of either mobility or firepower
K Kill:	Complete loss of vehicle (vehicle damaged beyond repair).

As initially developed, the methodology utilized engineering drawings to determine the tank components (including crew personnel) that a projectile would encounter in passing through the target tank. Using this information, along with perforation and damage data from the tank tests, quantitative tank vulnerability in terms of probability of achieving a specific type of "kill" was calculated. To apply this method, called the "compartment kill" method, required laborious and time consuming hand calculations.

In the middle 1960's a significant step forward in the calculation of tank vulnerability to conventional hostile weapons was made when the "compartment kill" method was computerized. A combinatorial geometry technique was utilized to describe the tank target in terms acceptable to a high speed digital computer. By this technique the complex tank target is represented mathematically by a set of simple geometric shapes, or stated more precisely, by the locations and shapes of the various physical regions of the target in terms of the intersections and unions of the volumes contained in a set of simple geometric bodies. By employing this technique for describing the tank, together

scenario, tends to confirm the critical aspect of mobility. Visual sweeps were often conducted from light vehicles moving at relatively high speeds. It has been reported that visual detection accounted for 75% of the mines detected on roads.

The engineering solution to the mobility limitation of mine detectors is unfortunately much more involved and complex than the system analysis required demonstrate it. The antenna-ground separation distance, target signature and false alarm discrimination, and vehicle stopping distance to prevent target overrun, are but a few of the factors that need to be considered in conjunction with field requirements in order to solve the problem. Developmental efforts, however, are directed at these basic problems and "Sad Sack's" days of glory will soon be gone.

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with a computerized version of the basic vulnerability assessment method and hostile weapon dispersion data the "compartment kill" methodology was made suitable for use on a high speed digital computer. This methodology has seen extensive use since its development.

However, over the years since the time of the first extensive tank tests which form the foundation of the "compartment kill" methodology, various and significant changes in tank design have occurred. Advances have been made in firepower, mobility and protection. Some of these advances include stabilized fire control and gun systems, variable height hydropneumatic suspension systems, new engine transmissions, night vision devices, new and improved armor, and increased system sophistication in general. Not only have improvements in systems occurred but, in addition, the physical location of various components has changed. Consequently, these changes warranted the development of an improved tank vulnerability methodology that could account for the influence of the individual components. For this reason, among others, and to provide improved guidance in the combat vehicle design process, AVVAM-1 was developed.

Effort was started on AVVAM in June 1972 and the first version, AVVAM-1, was made available in February 1973. The new code is ideal for both armored vehicle vulnerability and antiarmor weapons design and analysis studies. This first version of AVVAM treats components and personnel subjected to penetration and/or perforation damage mechanisms. The attacking munition may be a shaped charge or kinetic energy projectile, or a shaped charge or Misznay-Schardin land mine. With additional effort the present model may be extended to include other damage mechanisms as well. Although originally developed for armored vehicles, the code is not restricted to armored vehicles - it may be employed to assess the vulnerability of any materiel.

AVVAM-1 is based on analytical evaluations of the damage inflicted on individual critical components and the aggregate effect of these damaged components on compartment and overall vehicle vulnerability. To do this, AVVAM-1 accounts for not only the damage inflicted on components in the direct line of fire (shotline) of the attacking munition but also the damage inflicted by armor spall and/or munition fragment sprays on components located away from the munition shotline. AVVAM-1 also accounts for the degrading (or possibly enhancing) effects on the spall and/or fragment sprays caused by components positioned between the armor and the critical components. Thus, the potential protection afforded critical components by intervening components is included in the AVVAM-1 calculational procedure, and so, the effect of intervening components in reducing, or increasing the vulnerability, of a target vehicle may be evaluated by using AVVAM-1.

The code actually consists of two major, individual codes. One code is concerned with the vehicle geometry and configuration and the components in the vehicle critical to its operation. The other code is concerned with the terminal ballistics and behind-the-armor effects of the attacking munition as well as the assessment of kill probability. These two major code divisions are physically separated. The vehicle description and critical component location and description functions

are performed by one code, while the munition-target interaction characterization and kill probability assessment functions are performed by another code. Separation of these functions in this manner facilitates design optimization and systems analyses studies. Target vehicle parameters and/or munition parameters can be varied with relative ease. A series of munition design iterations or whole weapons systems intended to defeat a given target vehicle can be processed and evaluated by AVVAM-1 to achieve an optimum design. On the other hand, a similar iteration process can be followed in the optimum design of an armored vehicle. In this latter process a whole variety of armor materials and configurations as well as internal components and their character, configurations, and locations may be processed and evaluated until an optimum combination is achieved that provides the required degree of invulnerability to the attacking munition.

AVVAM development is not expected to halt with the first version described herein. On the contrary, a continuing extension, improvement and validation process is envisioned to provide the most accurate, efficient and reasonable armored vehicle vulnerability analysis tool possible.

Description of AVVAM-1

As described previously, AVVAM-1 is composed of two major computer codes. One of these characterizes the target. The other code characterizes the munition-target interaction and performs the vulnerability evaluation. The target characterization code describes the target and identifies, locates and determines the presented area of critical components. It also provides information concerning components that are located between the vehicle armor and critical components.

To generate the target description information, AVVAM-1 employs the GIFT (Geometric Information For a Target) code. This GIFT code is an improved version of the existing MAGIC code (2). It is presently being documented. The identification, location and presented area determinations of critical components and the intervening component information is generated by a new subcode recently developed at BRL called RIP (Rays Initiated at a Point).

The second major code employed in AVVAM-1 encompasses the terminal ballistics of the attacking munition and the post-plate-perforation characteristics of plate spall or munition fragment sprays. In addition, this second code calculates the vulnerability of selected components within the vehicle as well as compartment vulnerability and overall vehicle vulnerability. The code was also recently developed at BRL. Because of its functions, it is called the P^3 and the C^3PKH (Post-Plate-Perforation and Component, Compartment and Combat Vehicle Probability of a Kill give a Hit) code.

In operation, AVVAM-1 selects critical components within the target and then evaluates the extent of damage and kill probability for each selected munition aimpoint in a given view of the target. It does this by determining the armor thickness in the direction of the attacking shotline of the munition, the number of interceding components between the vehicle armor and the critical component and then utilizes the behind-

the-plate characterization of a specific munition to calculate maximum, mean, and minimum kill probabilities given a hit for all or selected critical components within the vehicle. This whole process is accomplished by firing a selected number of parallel rays at a given attack angle and azimuth into the target. Each individual parallel ray then spawns new rays that are initiated at the munition exit point on the armor interior surface. These new rays are used to search out the vulnerable components, define their position, shielding, and presented area. Then the post-plate-perforation subcode, converts terminal ballistics input data into an expected number of hits into each of the vulnerable components and finally the C^3PKH subcode determines the probability of a kill of these components for the expected number of hits. The kill probabilities for all the vulnerable components within a given compartment are combined into compartment M, F, & K kills. In addition, overall values for M, F, & K kills of the whole vehicle are also determined.

A flow chart summarizing the operations of AVVAM-1 is presented by FIG. 1. In this figure Box 1 represents the target input. Box 2 is the RIP section, Box 3 is the P^3 section and Box 4 is the C^3PKH section. The C^3PKH section provides the output in terms of probability of a kill given a hit. Also indicated in the figure is Box 5 which indicates an iteration scheme that may be employed for multiple views. Since the sections represented by Box 1, 2, 3, and 4 provide the PK/H output for a single view, results for multiple views may be obtained by iterating between Boxes 2, 3, and 4 for each view desired.

The code operates as follows: The particular target description is entered through Box 1 on cards and the specific munition is inputed by cards through Box 3. Information for the P^3 section is handled by card input. After the target is described and the critical components identified, RIP then, for a single vehicle view, selects a starting point on the vehicle, fires a main ray at the starting point, and essentially determines the position, shielding, and presented area of all the critical components in the vehicle in relation to the shotline of the main ray. The C^3PKH code calls on the Post-Plate-Perforation code to supply the behind the plate spall data and main munition shotline information to include number of fragments, size, and speed of fragments. Next, it calculates the expected number of fragments to hit a given critical component and then the probability of killing that component given a hit. It does this for each critical component identified by the RIP code for the particular shotline selected. All the critical components are evaluated for the first shotline. The RIP code then moves to a new shotline (or shotpoint) and the maximum, mean, and the minimum probabilities of a kill given a hit are calculated for all the components in the view of the new shotline. This process is continued until the whole view of the vehicle is completed. At this point the output of the AVVAM code is the following: Maximum, mean, and minimum probability of a kill for each critical component in the vehicle, a set of compartment M, F, & K kill probabilities and overall vehicle view probability of M, F, & K kill values. During these calculations the C^3PKH code in conjunction with the P^3 code account for the mass and velocity attrition of the shotline and spall fragments as they perforate intercedent components between the exit point on the armor and the specific vulnerable component under evaluation at that time.

Description of Sensitivity Study

There are an abundance of variables in the attacking projectile-tank vulnerability analysis problem. These may be grouped into projectile, tank and model variables. For a specific projectile, a shaped charge projectile for example, the following noninclusive factors affect the terminal ballistic and behind-the-armor characteristics of the projectile:

liner cone material
liner cone base diameter
liner cone configuration
explosive weight
standoff
striking velocity
striking angle of obliquity

The characteristics that these factors affect include the foll~~owing eight~~ variables:

armor depth of penetration
spall cone axis-jet axis angle
fragment number spatial distribution
fragment mass spatial distribution
fragment speed spatial distribution
fragment mass-number distribution
fragment speed-mass distribution
fragment configuration.

Now, for purposes of this dicussion, the tank variables may be subdivided into armor variables and other-than-armor variables. The armor characteristics depend upon its fabrication technique (either rolled or cast) and its configuration. In the configuration category may be placed homogeneous armor and spaced armor. Homogeneous armor variables are: The material of construction (steel, aluminum, etc.) and thickness of the armor. Additional variables pertaining to spaced armor arrays include the number of plates in the configuration and their spacing (as well as material of construction and thicknesses). In the other-than-armor category are the character of the tank components and their location outside or inside the vehicle. Component placement is a function of the imagination of the designer. The variables that effect the character of the components are: their conditional probability for various kill categories, their equivalent steel thickness, and their contribution to overall tank kill catagories. Consequently, the number of tank variables is at least fourteen to sixteen.

Additional variables that play a big role in the application of AVVAM-1 concern the mathematical representation of the tank's geometry and configuration. These variables include (as a minimum) the following: the detail to which the tank is to be analyzed, the number of views of the tank to be evaluated, the overall grid size (or number of analytical firings into a particular view of the tank), and the number of rays fired at each critical component to delineate its shape, location, and shielding.

All this means that a relatively complete sensitivity study of tank vulnerability to a specific projectile type would essentially require an infinite number of variations. For economy the present study is concerned with a total of five variables. Three of these affect both projectile and armor behavior. The other two effect the tank behavior itself. The projectile type studied is the shaped charge. The factors studied that effect both the projectile and tank behavior are: average fragment number, average fragment mass, and average fragment speed. The tank variables studied are component conditional probability for a specific kill category and component equivalent steel thickness. A total of sixteen combinations of these variables were selected for study.

The object of this study is to illustrate, by an investigation of a limited set of parameters, typical results that may be obtained by employing AVVAM-1 in an operational analysis or systems effectiveness study for systems acquisition decisions.

Results and Discussion

Figures 2 through 6 illustrate the trends in some of the results of the study. It should be emphasized here that these results correspond to a single, specific tank design and should not, at this time, be generalized. More work needs to be accomplished before generalizations could possible by made. However, a knowledge of the present results should be instructive. In all these figures normalized kill probability, $\overline{P}_k$, is plotted versus the various variables studied. Here, normalized kill probability relates the kill probability for a given set of values of the variables to the highest kill probability calculated i.e., the worst case condition for the tank considered in the study. Furthermore, the abscissas of these figures represent normalized values of the independent variables. This means that all the independent variables are presented relative to a given set of basic values of these variables. This basic value set corresponds to the present tank design and the behind-the-armor spall caused by a typical antitank shaped charge projectile. In the figures the baseline spall condition used as the norm for the various calculations is represented by N, M, and S. N, M, and S are respectively the total average number, average mass and average speed of the spall fragments produced behind the basic armor configuration by the baseline shaped charge munition. ET represents the baseline set of tank component equivalent steel thicknesses. Component equivalent steel thickness is a measure of the ballistic shielding provided by a tank component. The higher this value the harder it is for a spall fragment to perforate the component. PKH is used to represent the baseline set of component conditional kill probability values.

The influence of fragment mass on kill probability is illustrated by Fig. 2. The curve in this figure corresponds to the case in which the speed and number of fragments, component equivalent steel thickness, and component conditional kill probability set are maintained constant at the baseline values of S, N, ET and PKH, respectively. As indicated by the figure (and as to be expected) the normalized kill probability increases with increase in fragment mass. The curve is quite steep for $\overline{M}$ below 4 to 10 and begins to level off beyond $\overline{M}$ = 10 to 20. $\overline{P}_k$ increases

approximately 65% as the normalized fragment mass increases from 1 to 10. Although at $\bar{M} = 10$ a tenfold increase in $\bar{M}$ only yields about a 20% $\bar{P}_k$ increase.

Figure 3 shows the variation in normalized kill probability with normalized number of fragments. Component equivalent steel thickness and component conditional kill probability remain constant in all four curves shown. Curve A corresponds to the baseline fragment mass (M) and speed (S) while curve B corresponds to the same values of the variables as in A but with four times the baseline fragment mass (4M). Curve C corresponds to the same values of the variables as in A except the fragment speed is four times that of A (4S). Curve D is drawn for both four times the fragment mass (4M) and four times the fragment speed (4S) of curve A. Again, like the variation in kill probability with fragment mass illustrated by Fig. 2, Fig. 3 shows that kill probability increases with the number of fragments produced behind the armor. This increase, 42% for the baseline case of curve A from N = 1 to 4, is the same as the $\bar{P}_k$ increase with normalized fragment mass shown by Fig. 2. In Fig. 2 fragment number is kept constant at $\bar{N}$ while the normalized fragment mass is varied, and from $\bar{M} = 1$ to 4 the $\bar{P}_k$ increase is 42%.

Figure 3 also illustrates the relative influence of fragment mass and speed. By comparing curves B and C with curve A, it is seen that behind-the-armor fragments with four times the speed of the baseline case result in a higher normalized kill probability than fragments of the same speed as the baseline case but with four times the mass. Curve C, which shows the effect of higher speed, ranges from $\bar{P}_k$ equal to 74% to 32% higher than the baseline case of curve A while curve B, which represents the effect of higher fragment mass only ranges from 42% to 23% higher than curve A. This shows that the influence of fragment speed on kill probability is greater than is the influence of fragment mass. This situation is to be expected particularly if tank kill probability were a direct function of fragment kinetic energy. However, the effect of fragment speed (over the range studied) is only 1.4 to 1.75 times greater than the effect of fragment mass. This is much less than the factor of 5 which would result if tank kill probability were a direct function of kinetic energy. Even so, this means that tank armor with the ability to limit fragment speed more than fragment mass should be more effective in achieving a lower overall tank kill probability than armor designed more toward limiting fragment mass.

The effect of an equal (fourfold) increase in both fragment mass and speed is illustrated by curve D of Fig. 3. In this case the figure shows that the number of fragments exerts little influence on P_k. A fourfold increase in the number of fragments only yields a 7% increase in $\bar{P}_k$. This condition is probably dependent upon the existence of a minimum, or threshold, number of fragments. Below this threshold number kill probability most likely decreases rapidly with decreasing numbers of fragments.

Figure 4 clearly illustrates the influence of normalized fragment speed on normalized kill probability for two cases. The upper curve corresponds to baseline case values of fragment number and mass, component equivalent steel thickness and component conditional kill probability. The lower curve corresponds to these same constant parameter values except the component equivalent steel thickness is double the upper curve. As indicated, tank kill probability increases significantly with fragment speed. This increase is 74% for the upper curve and 119% for the lower curve over an increase in $\bar{S}$ from 1 to 4. Fig. 4 also demonstrates that an increase in fragment speed can be offset to a limited degree by increasing the equivalent steel thickness of components that are located between the tank armor and the critical components. This effect is discussed in more detail in the following.

The role of the ability of components to provide protection for critical components they may shield is demonstrated to some extent by Fig. 5. In this figure, normalized kill probability is plotted as a function of normalized component equivalent shielding thickness for fragments with the baseline speed (lower curve), and for fragments with four times the baseline speed (upper curve). The figure shows that, for the particular combination of critical component character, relative component placement, number, mass and baseline speed of fragments studied, the normalized component equivalent shielding thickness has significant effect on the kill probability over the range of component equivalent shielding thicknesses considered. As to be expected, kill probability decreases with an increase in component equivalent steel shielding thickness. This decrease is 32% for the lower curve and 14% for the upper curve as $\widehat{ET}$ is doubled from 1 to 2. Figure 5 also illustrates that an increase in component equivalent shielding thickness can be employed to offset to some extent the increase in $\bar{P}_k$ due to increased fragment speed. For example, if fragment speed is quadrupled, the $\bar{P}_k$ increases from about .496 (lower curve) to about .864 (upper curve) for a normalized component equivalent shielding thickness equal to one. This is a 74% increase in $\bar{P}_k$. However, if added shielding is provided the critical components by doubling the $\widehat{ET}$, the resultant $\bar{P}_k$ is about .74. This is only 49% above the initial value of .496 as compared with the 74% increase that would otherwise occur if the fragment speed were quadrupled without doubling the normalized component equivalent shielding thickness. The net savings then in $\bar{P}_k$ is 15%. This shows that decreased tank kill probability can be achieved by increasing the effective shielding thickness, or ballistic "hardness", of noncritical components placed between the basic tank armor and critical components. It also serves to demonstrate that this effect can be characterized quantitatively by AVVAM-1.

Figure 6 shows the effect of component conditional kill probability on tank kill probability for constant values of the baseline case. As indicated, overall tank kill probability increases with increasing probability that its critical components are killed if they are hit by the behind-the-plate fragments. Over the range of normalized component conditional kill probability from 0.5 to 1.0 the normalized tank kill probability increases 23%. This is a highly significant increase. It is the highest of all the rates of change of normalized kill probability found for variations in the baseline fragment and tank component independent variables studied.

The rate of change of normalized tank kill probability with respect to a particular variable (the slopes of the curves in Figures 2 through 6) indicates the sensitivity of the tank kill probability to the variable. Thus, the relative values of these variations indicate the relative sensitivity of the tank vulnerability to these variables. The following is a list of these variations in order of decreasing value over the range of normalized number of fragments, mass, speed, and component equivalent steel shielding thickness from 1 to 2 and normalized component conditional kill probability from 0.5 to 1, all obtained for the baseline conditions:

$$\frac{d\,\overline{P}_k}{d\,\overline{P}_{K/H}} = 0.186$$

$$\frac{d\,\overline{P}_k}{d\,\overline{ET}} = -0.159$$

$$\frac{d\,\overline{P}_k}{d\,\overline{S}} = 0.123$$

$$\frac{d\,\overline{P}_k}{d\,\overline{N}} = 0.070$$

$$\frac{d\,\overline{P}_k}{d\,\overline{M}} = 0.069\ .$$

From this list it is easily seen for the conditions studied that the tank vulnerability is most sensitive to the characteristics of its components and is least sensitive to the attacking shaped charge behind-the-armor fragment number and mass characteristics. The sensitivity of the tank's vulnerability to its components' characteristics at 0.186 and -0.159 is more than double its sensitivity to the number and mass of fragments produced by the baseline shaped charge munition. Therefore, slight variations in the characteristics of the tank components both in vulnerability to ballistic damage from behind-the-armor fragments and in the ability of noncritical components to provide ballistic shielding for the components critical to the tank's mission can be expected to cause large variations in the tank's overall vulnerability.

This situation may be used to advantage in guiding armored vehicle design. Attention given during the design and selection of critical components to achieving modest increases in vulnerability reduction of these components promises potential for achieving large benefits in reducing the tank's overall vulnerability. This is equally true for selection of and design improvements to components that would increase their resistance to ballistic perforation. Here again modest increases in ballistic perforation resistance (equivalent steel thickness) show the potential for significant gains in reducing tank vulnerability.

On the other hand, since the tank vulnerability is relatively insensitive to variations in both the number and mass of the behind-the-armor fragments, it appears that little is to be gained by concentrating on these factors. Furthermore any gain in this area would require considerable effort. Large reductions in either the number of fragments or their masses are apparently required to cause a significant reduction in the overall vulnerability of the tank studied here.

A more fruitful area for tank vulnerability reduction efforts than controlling the number and mass of fragments is pointed out by the sensitivity results. This area is fragment speed. Since the tank vulnerability is almost as sensitive to fragment speed as it is to the characteristics of its components, significant potential for meaningful vulnerability reduction appears to lie in reducing the speed of behind-the-armor fragments. Therefore, this suggests work should be done on the basic tank armor (if feasible) to reduce the speed of the fragments forced out of the back surface of the armor.

It should be kept in mind that the results obtained in this study and discussed here concern a specific tank, a specific hostile munition, and a limited investigation of a small number of parameters involved in tank vulnerability. It may be possible that the order and degree of the influence of of the variables studied could be widely different under different conditions, that is, if the range of the variables studied were widened or if a narrower range were investigated at extreme ends of the possible spectrum of the variables. In any event, the case presented here provides a sample illustration of the potential applications of AVVAM-1 to weapons systems effectiveness studies and the systems acquisition process.

Summary

A general description of AVVAM-1 (Armored Vehicle Vulnerability Analysis Model - First Version) along with the results of a limited tank vulnerability sensitivity study obtained by use of AVVAM-1 have been presented and discussed. This sensitivity study has been performed and reported here to illustrate, by means of a limited study, the potential applications of this new model to weapons systems effectiveness studies and the systems acquisition process.

References

1. Haskell, D. F. and M. J. Reisinger, "AVVAM-1, Armored Vehicle Vulnerability Analysis Model - First Version", Ballistic Research Laboratories, BRL IMR No. 85, February 1973.

2. "MAGIC Computer Simulation", Volumes I and II, Naval Weapons Center Technical Note 4565-3-71, Vol. I and II, May 1971.

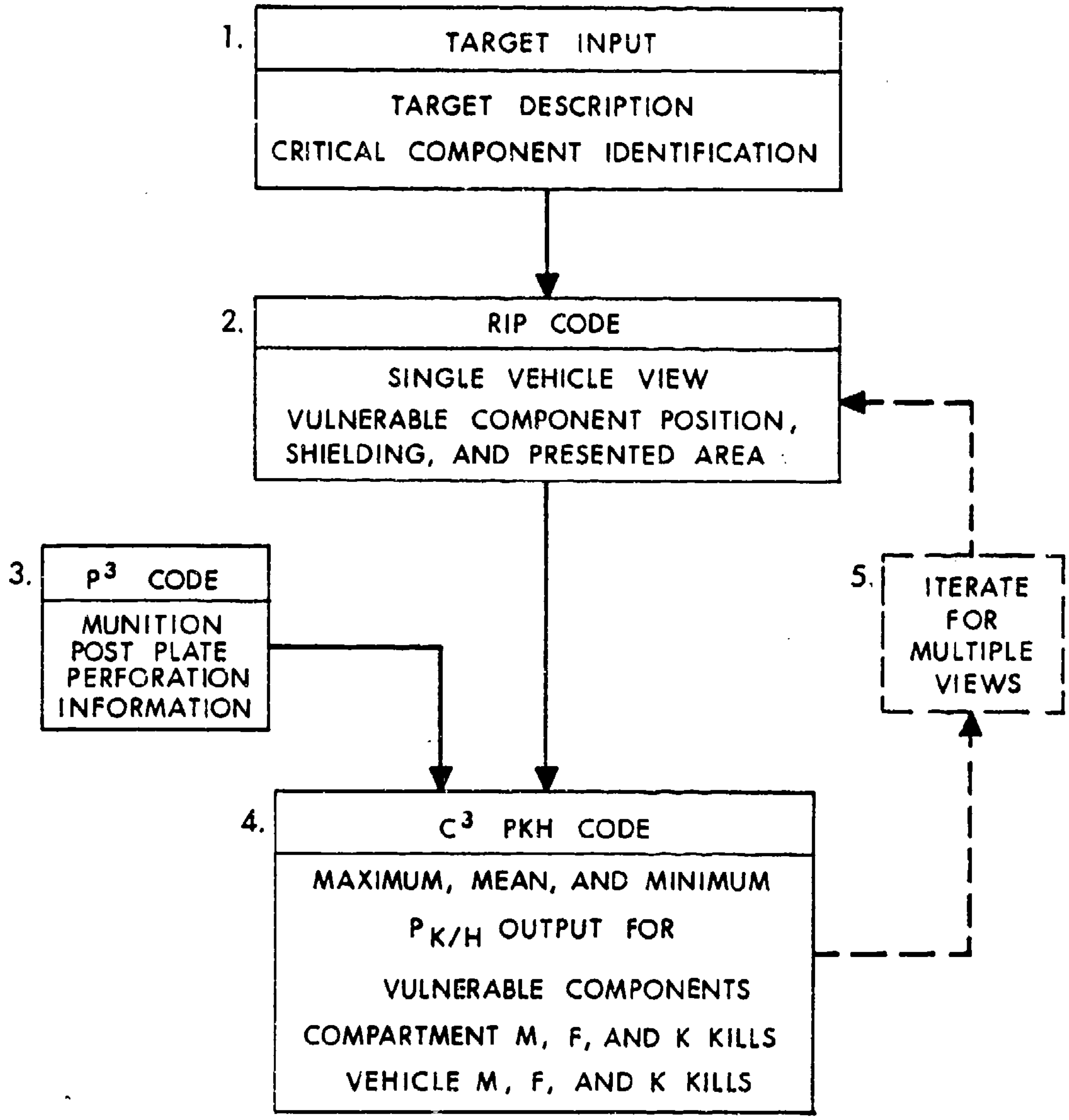

Figure 1. AVVAM-1 Code Summary Flow Chart

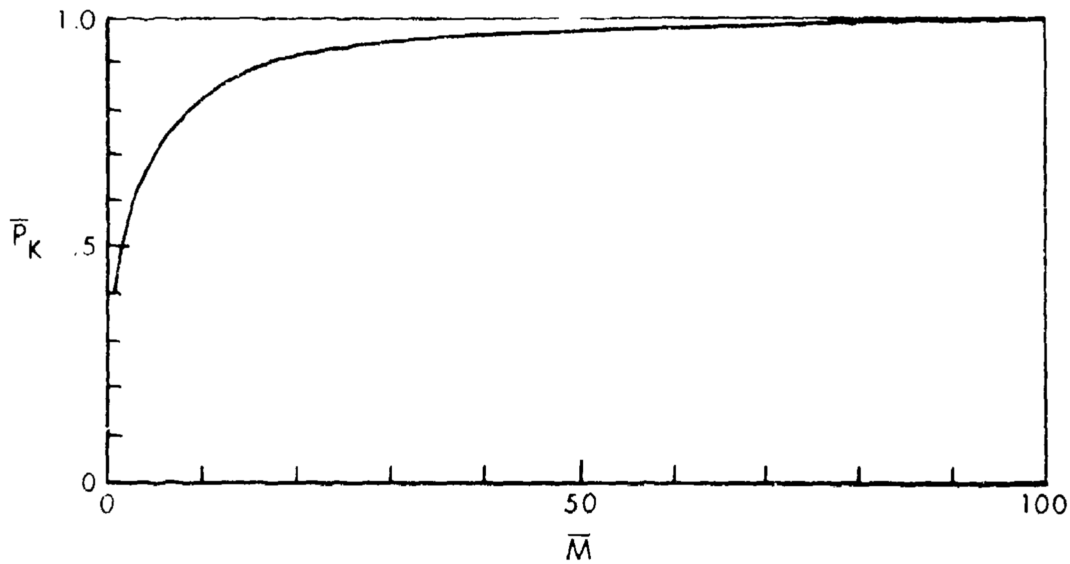

Figure 2. Effect of Normalized Fragment Mass on $\overline{P}_K$

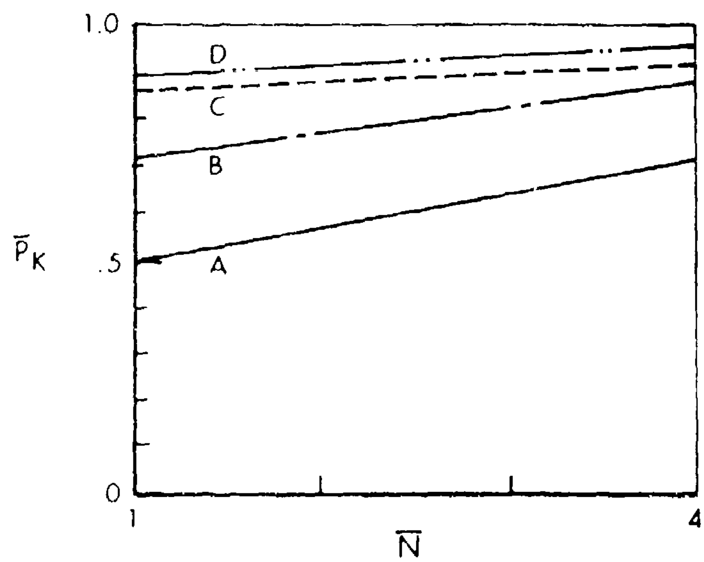

Figure 3. Effect of Normalized Number of Fragments on $\overline{P}_K$.

CURVE A: M, S, ET, PKH
B: 4M, S, ET, PKH
C: M, 4S, ET, PKH
D: 4M, 4S, ET, PKH

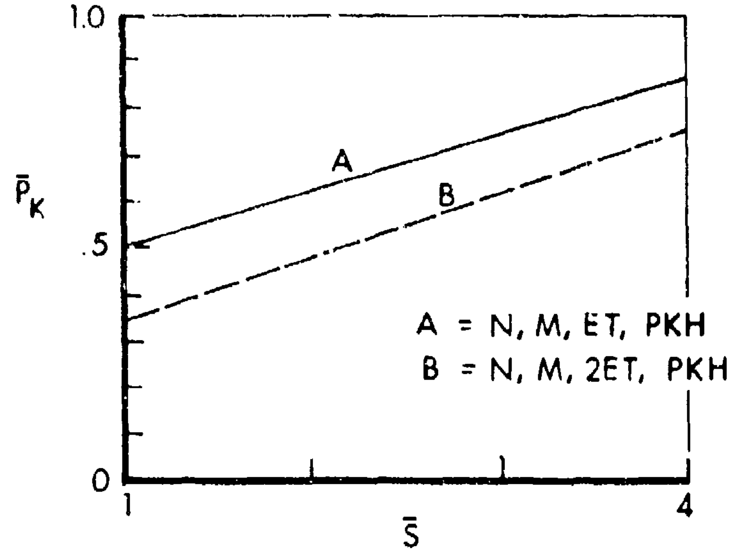

Figure 4. $\bar{P}_K$ Variation with Normalized Fragment Speed

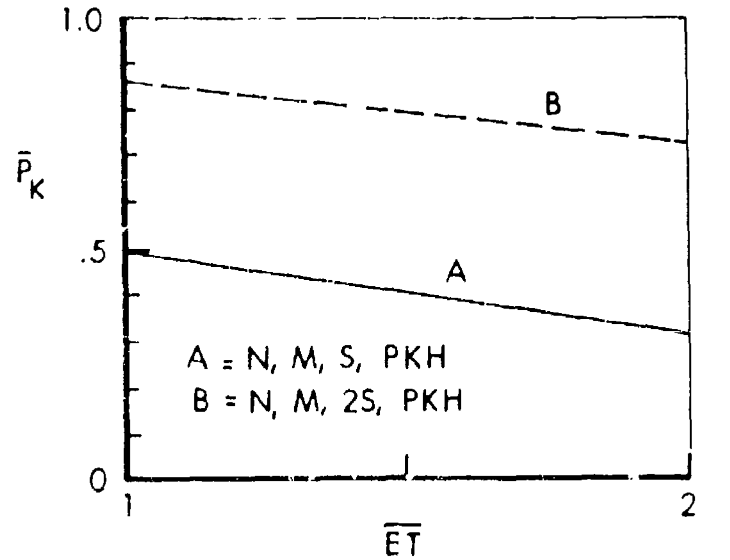

Figure 5. Effect of Normalized Equivalent Shielding Thickness on $\bar{P}_K$

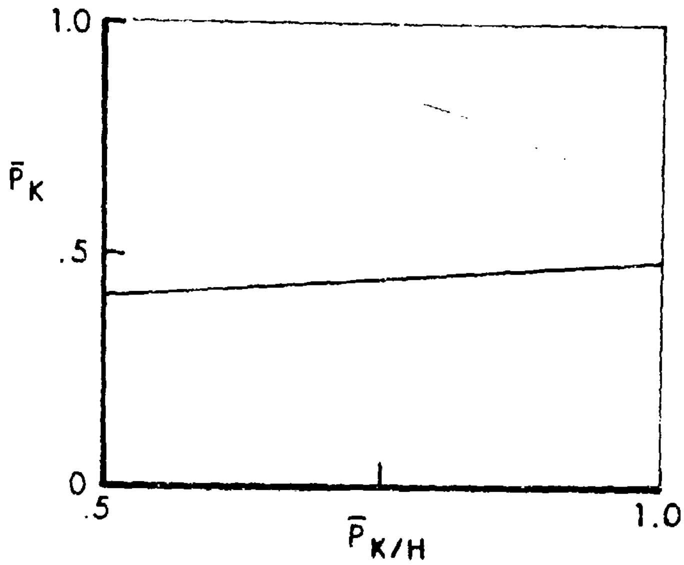

Figure 6. $\bar{P}_K$ Variation with Normalized Component Kill Probability

SENSITIVITY ANALYSIS OF A WEAPON EFFECTIVENESS MODEL

by

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Several publications have been issued by the Joint Munitions Effectiveness Manual/Surface-to-Surface (JMEM/SS) Methodology and Evaluation Working Group presenting the effectiveness of various US Army mortar and artillery weapon systems against personnel and materiel targets. The Joint Munitions Effectiveness Manuals have been produced under the auspices of the Joint Technical Coordinating Group/Munitions Effectiveness for the purpose of providing the DOD community with a uniform source of weapons effects data. The effectiveness data included in these manuals incorporate munitions lethality, delivery accuracy, reliability and environmental effects against a representative spectrum of targets. As one of its assignments as a member of the JMEM/SS Methodology and Evaluation Working Group, the Concepts & Effectiveness Division of Picatinny Arsenal was tasked to conduct a sensitivity study to answer the following question: Considering the variability and uncertainties in the inputs used to compute the JMEM/SS effectiveness numbers for indirect fire systems, how sensitive are the answers to "errors" in these input values? This paper will describe the sensitivity analysis conducted on one of the US Army's 155mm howitzer weapons.

Among the basic input values used to compute the effectiveness of fragmentation weapons are the following:

V_F - Fragment Velocity

N_F - Numbers of Fragments

SF - Fragment Shape Factor

ω - Angle of Fall

MBH - VT Fuze Mean Burst Height

DENS - Biomass Density (Vegetative Environments)

BHD - Fuze Burst Height Distribution in Environment

BE - Precision Error (Ballistic, Round-to-Round, etc.)

AE - MPI Error (Aiming)

L/2 - Munition Centroid Distance (For Ground Burst)

The above parameters can be classified as measured (or experimentally determined) or computer-generated based on "real life" models.

For example, for a given Charge and Quadrant Elevation, the shell will have a nominal range, terminal angle of fall and terminal velocity, determined from a Six-Degree-of-Freedom Trajectory Computer Program. While these parameters are normally considered "known" in an absolute sense, one can expect a certain degree of variability due to tolerances in shell manufacture, propellant weight differences, atmospheric conditions, etc.

Another example of this expected variability is evident in the JMEM treatment of environmental effects. The JTCG/ME Degradation Effects Program has defined a series of four "standard" forests (Temperate; Tropical Rain; Coniferous; and Jungle Tangle) which are felt to be "representative" of the range of forest types that exist throughout the world. Although the DEP Forests are now established as "fixed" entities (overall size, number and location of trees, root structure, diameter and taper of trunk, branches, etc.), this is not to be construed as meaning that the effectiveness calculated for, say, the DEP Temperature Forest will be applicable to all temperate forests in which the weapon in employed. Thus, pertubations of the parameters defining the "standard" environment will serve as an indication of the variability in weapon effectiveness when used in a world-wide context.

At the outset of the study, members of the JMEM/SS and other outside "experts" were requested to review the previously defined input parameters and to indicate the degree of confidence they would attach to the numbers defining these parameters. Table 1 summarizes the consensus of opinion on this spread in terms of either an absolute plus-or-minus value about the indicated or a plus-or-minus percentage about the indicated value; these, in turn, were interpreted to be $\pm$ 2σ variations about the mean value of a normal distribution of the input parameter.

Other "fixed" conditions which were felt to have a bearing on the problem are indicated as follows:

Projectile Caliber

Fuze

Personnel Target Posture

Environment

Angle of Fall

Target Size

Weapon Formation

No. of Volleys Fired

Table 2 presents the conditions selected for the analysis, i.e., those for which Expected Fraction Casualties ($\overline{F}_c$) values were obtained using accepted JMEM methodology and computer programs. The problem then

resolves itself into finding a measure of the total variability of $\overline{F}_c$ due to the individual variabilities of all the input parameters in combination.

If $\overline{F}_c$ is a function of several input variables, i.e.,

(1) $\overline{F}_c = f[x_1, x_2, \ldots, x_i, \ldots x_n]$, we define S_{x_i} as the Sensitivity Coefficient relating the fractional change in $\overline{F}_c$ to the fractional change in x_i. Mathematically, the Sensitivity Coefficient may be written as:

$$(2) \qquad S_{x_i} = \frac{\frac{\Delta F_c}{F_c}}{\frac{\Delta x_i}{x_i}}$$

The total error, in terms of F_c, is defined as:

$$(3) \quad \text{Total Error} = \left(\frac{\sigma F_c}{F_c}\right)^2 = \sum_{i=1}^{n} \left(S_{x_i} \frac{\sigma x_i}{x_i}\right)^2$$

The standard deviation of $\overline{F}_c$, expressed as a fraction of its mean value, is:

$$(4) \qquad \sigma F_c \text{ (As Fraction)} = \left[\sum_{i=1}^{n} \left(S_{x_i} \frac{\sigma x_i}{x_i}\right)^2\right]^{1/2}$$

A large number of $\overline{F}_c$ computations were performed for the "constant" input conditions of Table 2, wherein each of the input variables (x_i) of Table 1 was perturbed by the indicated $\pm$ 2 σx_i. The ΔF_c was determined as the average of the two results and the contribution of each independent input parameter was computed as:

$$(5) \qquad \sigma F_c\ (x_i) = S_{x_i} \frac{\sigma x_i}{x_i} = \frac{1}{F_c} \quad \frac{\Delta F_c}{\Delta x_i} \quad \sigma x_i$$

The σF_c index of total variability was determined as the square root of the sum of squares as shown by Equation (4). Table 3 presents a summary of some typical results for the PD-fuzed projectile, a volley size of 12 (72 rounds), and a prone personnel target radius of 100 meters; both the individual (Equation 5) and total (Equation 4) variabilities are presented. Table 4 lists some of the results for a VT fuzed projectile; in this case, only the open and marsh grass environments were evaluated.

If we consider a "critical" variable one which contributes an absolute value of 5% or more of the total σF_c, i.e.,

$$(6) \quad \sigma_{F_c} (x_i) \geq .05, \text{ then}$$

Table 5 is a listing of these critical parameters for the $\overline{F}_c$'s computed per Tables 3 and 4 and for the two extremes of target sizes selected for the study (R_T = 50m and R_T = 150m: small and large, respectively). It is seen that the fragmentation characteristics of the shell (viz., numbers of fragments and fragment velocities) are "critical" along with the environment-dependent variables (biomass density and the PD fuze burst height distribution in Temperate Forest). When we examine the conditions of Table 2, we find that within the constraints of the study, $\overline{F}_c$ variability trends are essentially independent of the following:

Weapon Spacing (Star or Lazy-W Formation)

Target Posture (Prone or Standing)

Type Fuze (PD or VT)

Volley Size

In general, the following "constant" factors produce discernable trends in the magnitude of the variability of the weapon effectiveness index: Environment, Target Size, Angle of Fall (for forest only). These trends may be stated as follows:

1. The Marsh Grass and Temperate Forest environments increase the magnitude of σF_c in that order
2. The individual and total sensitivities increase as target size decreases
3. Lo-angle fire in Temperate Forest produces the highest $\overline{F}_c$ variability.

For the combinations of target size, fuze type, angle of fall and environment specified in Tables 3 and 4, Table 5 presents a summary of the ranges and average values of the individual σF_c (x_i)'s as determined from Equation (5). The x_i's here are listed in order of their decreasing effect upon the total σ_{F_c}.

Figure 1 is a histogram of the frequency function of the total σ_{F_c} for the approximately 300 cases investigated for varying target sizes, weapon formations, environments, fuze types, target postures, etc. (It will be remembered that for each of these cases, $\overline{F}_c$'s were computed at the $\pm$ 2 σ_{x_i} extremes of each of the x_i input variables; thus, the chart represents over 6000 separate computations!) From this information, an average σ_{F_c} of 12% is computed. This can be interpreted as stating that, within the uncertainties associated with the input parameters used to compute Expected Fraction Casualties ($\overline{F}_c$) for fragmentation munitions, the "true" F_c can be expected to lie between $\pm$ 25% of the computed value.

TABLE 1

EXPECTED SPREAD IN VALUES ASSIGNED TO INPUT PARAMETERS

Variable x_i	$\pm 2\sigma_{x_i}$
V_F - Fragment Velocity	20%
N_F - Number of Fragments	20%
SF - Fragment Shape Factor	10%
L/2 - Projectile Centroid Location	6"
ω - Angle of Fall	2°
BE - Precision Error	25%
AE - MPI Error	25%
MBH - VT Fuze Mean Burst Height (Open and Grass)	2 meters
DEN - Biomass Density	50%
BHD - PD Fuze Burst Height Dist'n (Forest)	50%

TABLE 2

CONDITIONS FOR JMEM/SS SENSITIVITY ANALYSIS

PROJECTILE	:	155mm Howitzer
FUZES	:	M557 PD and M514 VT
TARGET	:	Personnel (Prone and Standing)
ENVIRONMENTS	:	Open; DEP Marsh Grass; DEP Temperate Forest
ANGLE OF FALL	:	20° and 47°
TARGET RADII	:	50; 100; 150 meters
WPN FORMATION	:	Lazy-W and Star
NO. VOLLEYS	:	1, 6, 12, 24

TABLE 3

INDIVIDUAL AND TOTAL $\overline{F}_c$ VARIABILITY (IN%)

PRONE R_T = 100m PD FUZE 12 VOLLEYS LAZY-W

x_i	V_F	H_F	SF	L/2	ω	BE	AE	MBH	DEN	BHD	Total σF_c
σx_i	10%	10%	5%	3"	1°	12.5%	12.5%	1m	25%	25%	
ω = 20°											
Open	4	6	1	4	0	1	3	--	--	--	9
Marsh Grass	8	6	2	3	1	1	3	--	6	--	12
Temperate Forest	4	7	1	2	0	2	3	--	3	21	23
ω = 47°											
Open	3	6	1	6	1	4	4	--	--	--	10
Marsh Grass	7	6	2	5	1	3	4	--	6	--	13
Temperate Forest	3	7	1	4	1	3	4	--	3	6	12

TABLE 4

INDIVIDUAL AND TOTAL $\overline{F}_c$ VARIABILITY (IN%)

PRONE R_T = 100m VT FUZE 12 VOLLEYS LAZY-W

	x_i	V_F	N_F	SF	L/2	ω	BE	AE	MBH	DEN	BHD	Total
ω = 20°	σx_i	10%	10%	5%	3"	1°	12.5%	12.5%	1m	25%	25%	σF_c
Open		5	6	1	--	0	0	3	4	--	--	9
Marsh Grass		7	6	3	--	1	0	3	7	8	--	15
ω = 47°												
Open		4	6	1	--	1	3	4	4	--	--	10
Marsh Grass		6	6	2	--	1	3	4	5	7	--	14

TABLE 5

RANGE OF AND AVERAGE $\sigma_{F_c}(x_i)$ - IN%

VARIABLE x_i	σ_{x_i}	RANGE OF $\sigma_{F_c}(x_i)$ MIN.	MAX.	AVG $\sigma_{F_c}(x_i)$
BHD	25%	6	24	14
N_F	10%	6	7	6
DENS	25%	3	8	6
V_F	10%	3	8	5
MBH	20%	2	7	4
L/2	20%	2	7	4
AE	12.5%	2	6	4
BE	12.5%	0	5	2
SF	5%	1	3	2
ω	5% & 2%	0	2	1

PRONE PERSONNEL

VOLLEY SIZE = 12

HISTOGRAM OF RESULTS

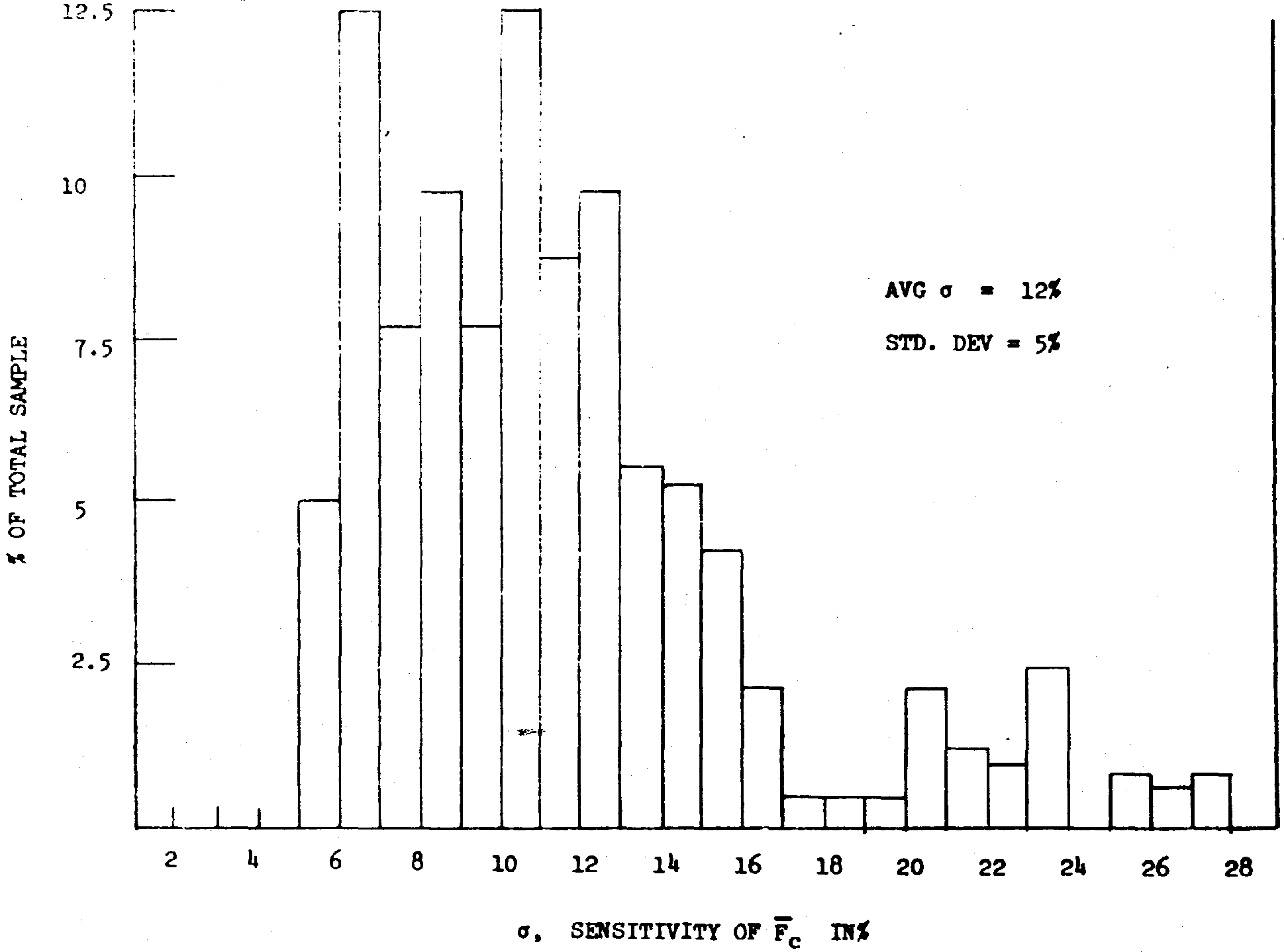

Fig. 1

AD P000618

A MATHEMATICAL MODEL FOR ASSESSMENT OF CHEMICAL WEAPONS SYSTEMS

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I. INTRODUCTION.

This paper is concerned with the development of an analytical mathematical model, as opposed to a Monte Carlo or simulation model, that is applicable to the assessment of area coverage potential and casualty producing potential of chemical weapons systems.

The model can be used to obtain probability functions that describe the distribution of doses, dosages and casualties over populated finite area targets resulting from attacks with toxic chemical weapons systems. Once the probability functions have been specified, then all relevant information associated with the area coverage potential and the casualty producing potential of a given chemical weapon system can be obtained from these functions.

In order to construct the model it is necessary that the following functional components of the model be expressed analytically.

A. Distribution of Target Personnel.

The positions of people on a specified target area is assumed to be a random variable (X,Y), and the associated probability density denoted by $\omega(x,y)$ is defined on the finite domain T_A the given target area.

B. Dose Intake Function.

The dose intake function denoted by $B(t)$ measures either the quantity of agent inhaled per unit time or the quantity of agent penetrating the skin per unit time, for an arbitrary person located at the target point (x,y). The intake function is dependent upon the activity level or level of physical exertion.

C. Agent Concentration Function.

The concentration of toxic agent at an arbitrary point (x,y,t) is denoted by the function $\phi(x,y,t)$. The function ϕ is continuous and nonnegative.

D. Distribution of Agent Dissemination Devices or Source Points.

The location of munition impact points or agent emission source points are assumed to be random variables (U,V) with the associated probability density function denoted by $f(u,v)$, defined on some specified finite impact region I_A. The distribution of the source points are related to the particular munition delivery system being employed.

E. Dose-Response Function.

The dose-response function defines the probability of an arbitrary person becoming a casualty when that person has taken in a dose of magnitude D. The dose-response function is denoted by P(D), it is nonnegative and nondecreasing on its domain of definition.

II. FORMULATION OF MODEL.

The formulation of the model is based on a collection of well-known definitions and theorems of mathematical statistics. Those readers interested in formal proofs of the theorems are referred to the bibliography at the end of this paper.

A. Basic Definitions and Notations.

1. Definition one.

The dose at any point (x,y) after an elapsed time T, for a single toxic submunition impacting at t=o, at point (u,v), for a person located at point (x,y) and having an intake rate B(t) is defined by the relation given by equation

$$G(x-u,y-v,T) = \int_{o}^{T} B(t)\phi(x-u,y-v,t)dt \qquad (1)$$

where ϕ is the component function defining the concentration of agent at (x,y) for any instant t, resulting from and impact at point (u,v). The point (x,y) lies in some target T_A, and the point (u,v) lies in some impact are I_A. If the function B is unity for all values of t then the function G measures the dosage at point (x,y).

2. Definition two.

The accumulated dose at point (x,y) after an elapsed time T, for N simultaneously impacting submunitions with impact points denoted by the set $\{(u_k,v_k):(k=1,\ldots,N)\}$ is defined by equation

$$D(x,y;T) = \sum_{k=1}^{N} G(x-u_k,y-v_k;T) \qquad (2)$$

where D is the accumulated dosage at (x,y) for B(t)=1, otherwise D represents the accumulated dose at (x,y).

3. Definition three. (Dose-response Function)

The probability of an arbitrary person located at point (x,y) becoming a casualty when that person has taken a quantity of agent

of magnitude D is defined by equation

$$P(D) = \int_{o}^{D} 2\alpha[\alpha^2+x^2]^{-1}\, dx, \quad o \leq D < \infty$$

or (3)

$$P(D) = (2|\pi) \arctan (D\alpha^{-1}).$$

The parameter α, in equation (3), is the LD50 value for the particular agent being considered.

B. Derivations.

The accumulated dosage or dose D, for N-submunitions, is a random variable having an associated probability density function denoted by $h_N(d)$. The r-th moment, about the origin, of variate D is given by equation

$$\lambda_r = E(D^r) = \frac{\partial^r}{\partial\theta^r} \prod_{k=1}^{N} E[e^{\theta G(x-u_k,y-v_k;T)}] \Big|_{\theta=o}, \tag{4}$$

or

$$\lambda_r = \frac{\partial^r}{\partial\theta^r} \int_{T_A} [\int_{I_A} f(u,u)e^{\theta G(x-u,y-v;T)}dudv]^N \omega(x,y)dxdy \tag{5}$$

The r-th moment λ_r of variate D, for N-submunitions, can be expressed in terms of the r-th moment m_r for one submunition. In particular, the first five of these moments can be obtained by evaluating the following relations:

$$m_r(D) = \int_{T_A} \int_{I_A} G^r(x-u,y-v;T)f(u,v)\omega(x,y)dudvdxdy$$

$$\text{for} \quad (r=0,1,2,3,4) \tag{6}$$

and

$$\left.\begin{aligned}
\lambda_0(D) &= 1\\
\lambda_1(D) &= Nm_1\\
\lambda_2(D) &= Nm_2+N(N-1)m_1^2\\
\lambda_3(D) &= Nm_3+3N(N-1)m_1m_2+N(N-1)(N-2)m_1^3\\
\lambda_4(D) &= Nm_4+4N(N-1)m_1m_3+3N(N-1)m_2^2+6N(N-1)(N-2)m_1^2m_2\\
&\quad +N(N-1)(N-2)(N-3)m_1^4
\end{aligned}\right\} \tag{7}$$

The density function $h_N(D)$, whose first five moments are given by equations (6) and (7), is defined on the interval $[0,Nc]$, where the constant c represents the maximum value of the function G over the target area T_A for the specified time period, $t\varepsilon[0,T]$.

These moments of the dose or dosage distribution, over the target area, may be used to construct the probability density function $h_N(D)$ for $D\varepsilon[0,Nc]$. The mathematical form selected for the approximation is as follows:

$$h_N(D) = W(D) \sum_{i=o}^{n} c_i q_i(D), \text{ for } D\varepsilon[0,Nc] \tag{8.0}$$

where

$$W(D) = \frac{\Gamma(a+b+2)}{\Gamma(a+1)\Gamma(b+1)(Nc)^{a+b+1}} D^a (Nc-D)^b. \tag{8.1}$$

The parameters a,b are determined by equations

$$a = (\lambda_2-\lambda_1^2)^{-1}[2\lambda_1^2-(1+\frac{\lambda_1}{Nc})\lambda_2] \tag{8.2}$$

and

$$b = (\lambda_2-\lambda_1^2)^{-1}[\lambda_1(Nc+\frac{\lambda_2}{Nc})-2\lambda_2]. \tag{8.3}$$

The polynomials $\{q_i(D)\}$ are orthogonal with respect to the weight function W(D) and are defined by,

$$q_i(D) = \sum_{r=o}^{i} A_{ir} D^r \tag{8.4}$$

for

$$A_{ir} = (Nc)^{-r}(-1)^{i+r} \sum_{j=o}^{r} \binom{i-j}{r-j} a_{ij} \tag{8.5}$$

with

$$a_{ij} = \binom{i+b}{j} \binom{i+a}{i-j}. \tag{8.6}$$

Then the coefficients $\{c_i\}$ needed for the expansion of equation (8.0) are computed from the relations given by equations

$$c_i = k_i \sum_{r=o}^{i} A_{ir} \lambda_r \tag{8.7}$$

and

$$k_i = \frac{i!(a+b+2i+1)\Gamma(a+b+i+1)\Gamma(a+1)\Gamma(b+1)}{(Nc)\Gamma(a+i+1)\Gamma(b+i+1)\Gamma(a+b+2)} \tag{8.8}$$

The probability density function associated with the distribution of casualties over the target area T_A can be obtained from equation (3) along with equation (8.0). The dose-response function, defined by equation (3), is a continuous monotonic increasing function and, therefore, possesses a unique inverse. Hence, the distribution function $L(p)$, relative to the variate D is

$$L(p) = \int_{o}^{\alpha \tan(\frac{\pi}{2}p)} h_N(D)dD \qquad (9.0)$$

So that the probability density function for the fraction of casualties is simply

$$\Psi(p) = \frac{d}{dp} L(p) = \frac{\pi\alpha}{2} h_N(\alpha\tan(\frac{\pi}{2}p))\mathrm{Sec}^2(\frac{\pi}{2}p) \qquad (9.1)$$

or

$$\Psi(p) = \frac{\pi\alpha}{2} [1+\tan^2(\frac{\pi}{2}p)]h_N(\alpha\tan\frac{\pi}{2}p) \qquad (9.2)$$

$$\text{for} \quad p\varepsilon[0, \frac{2}{\pi} \tan^{-1}(\frac{Nc}{\alpha})].$$

III. AN ILLUSTRATIVE EXAMPLE.

The following example has been selected to illustrate how the various aspects of the analytical model are applied and to permit a comparison of the model with Monte Carlo simulation results. The component functions that are selected, in this example, do not necessarily represent realistic mathematically descriptive functions associated with an actual chemical attack. However, the mathematical machinery utilized, in the example, would be the same for functions that are more accurately descriptive of physical situation.

It is anticipated that the general sequence of computations will summarize the salient features of the model and provide useful information for the purpose of constructing efficient computer programs or routines for evaluating the model.

ANALYTICAL APPROACH

The component functions and their parameters are as follows:

1. $B(t) = 1$, the breathing rate of all target personnel is taken to be one volume of air per unit time.

2. $$\phi(x,y;t) = \frac{Q}{2\pi} t\, e^{-\frac{1}{2}[x^2+y^2+2t]} \qquad (10.0)$$

$$\text{for} \quad x,y\varepsilon(-\infty,\infty),\ t\varepsilon(0,\infty)$$

The function Φ measures the concentration of toxic agent at any point (x,y) at time t, for a single submunition with impact point $(0,0)$, and Q the quantity of agent per submunition is taken to be 23.7782 milligrams.

3. $\omega(x,y) = (0.01)$, for $x,y\varepsilon[0,10]$ meters, (10.1)

$\omega(x,y) = 0$; otherwise,

the function ω (a uniform density function), denotes the density function for target personnel on the target area T_A. (T_A=100 square meters).

4. $f(u,v) = (0.01)$, for $u,v\varepsilon[0,10]$, (10.2)

$f(u,v) = 0$; otherwise,

the function f (a uniform density function), denotes the probability density function associated with the distribution of submunition impact points on the impact area I_A. (I_A=100 square meters).

5. $p(D) = \frac{2}{\pi} \tan^{-1}(\frac{D}{\alpha})$, $D\varepsilon[0,\infty]$ (10.3)

The function p measures the probability of obtaining a casualty for a dose of magnitude D, for a toxic agent with LD50 = α = 1 milligram.

6. T = 1 minute, the time after the attack in which casualties are considered.

7. N = 10, the number of submunitions used in the attack.

The required sequence of operations necessary for evaluating the model are:

1. Compute Dose Function G.

$$G(x,y;1) = \int_0^1 B(t)\phi(x,y;t)\,dt \tag{11.0}$$

$$G(x,y;1) = e^{-(0.5)(x^2+y^2)} \tag{11.1}$$

The maximum dose for a single submunition on the target T_A, during the time period of one minute, is c = 1 milligram.

2. Compute $m_r(D)$: (r=0,1,2,3,4).

$$m_r(D) = \iint_{T_A} \iint_{I_A} G^r(x-u,y-v)f(u,v)\omega(x,y)dudx\,dxdy \tag{11.2}$$

$$m_r(D) = [(0.01) \int_0^{10} \int_0^{10} e^{-\frac{r}{2}(x-u)^2} dudx]^2 \tag{11.3}$$

$m_0 = 1$
$m_1 = 0.05320534$
$m_2 = 0.02797102$
$m_3 = 0.01905879$
$m_4 = 0.01447965$

3. Compute $\lambda_r(D)$: (N=10).

$\lambda_0 = 1$

$\lambda_1 = .53205340$

$\lambda_2 = .53448294$

$\lambda_3 = .70031701$

$\lambda_4 = 1.10353721$

4. Compute Probability Density $h_N(D)$.

$$h_N(D) = A\, D^a\, (1-0.1\, D)^b,\ D\epsilon[0,10] \tag{11.4}$$

$a = .0129$
$b = 17.0246$
$A = 1.8276$

5. Compute Probability Density $\Psi(p)$.

$$\Psi(p) = B[1+\tan^2 \tfrac{\pi}{2} p][\tan \tfrac{\pi}{2} p]^a\ [1-0.1 \tan \tfrac{\pi}{2} p]^b \tag{11.5}$$

for $p\epsilon[0,.94]$

$B = 2.8708$

6. Compute Expected Fraction of Casualties.

$$E(p) = \int_0^{.94} p\Psi(p)dp$$

$E(p) = 0.05$

7. Compute Variance θ_r E(p).

$$Var[E(p)] = \int_0^{.94} p^2\Psi(p)dp - E^2(p)$$

$$Var[E(p)] = 0.0022 \tag{11.7}$$

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ON RELIABILITY GROWTH MODELING

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1. INTRODUCTION

Military weapon systems are becoming increasingly complex and are consequently requiring more resources in terms of time, dollars and manpower during their development programs in order to achieve their respective reliability requirements at the time of production. Attempts are made during the development programs to find and remove the design and engineering deficiencies to a point where certain levels of performance with respect to reliability and other requirements are met.

Before the development program begins the program manager is faced with the problem of how to allocate the available resources during development to insure that the required reliability will be met at least within the final stage of development. Also, after the development program has begun the program manager is equally concerned with estimating from test data (usually limited in quantity) the current system reliability and projecting the system reliability into the near future. That is, in terms of reliability, he is interested in "where it is" and "where it is going." The area of reliability growth modeling is a management tool directed toward those needs of the program manager.

Since it is usually assumed that the system reliability will increase during the development program, mathematical models describing this phenomenon have come to be called "reliability growth" models. Most of the reliability growth models considered in the literature assume that a mathematical formula (or curve), as a function of time, represents the reliability of the system during the development program. It is commonly assumed, also, that these curves are nondecreasing. That is, once the system's reliability has reached a certain level, it will not drop below this level during the remainder of the development program.

The central purpose of most reliability growth models includes one or both of the following objectives:

- Inference on the present system reliability;
- Projection on the system reliability at some future development time.

Consequently, based on prior experience on similar type systems, the program manager may choose a certain reliability growth model to help him plan the development program. After the development program has begun he may use this model and test data to monitor and project the reliability of the system and make necessary decisions accordingly.

As in any mathematical model, reliability growth models are idealizations. They are based on a number of assumptions that vary with the models and which are mathematical formulations of the growth

of reliability during development under certain conditions. There are innumerable ways in which reliability can grow during development and there are, of course, only a finite number of reliability growth models available. Consequently, a program manager cannot conduct the development program in just any fashion and have an existing reliability growth model available to him for estimation and prediction purposes. The manner in which the development program is managed and the choice of the reliability growth model are, therefore, dependent.

Many reliability growth models are parametric. That is, these models have certain parameters which are unknown and must be estimated from test data generated during the development program. Of interest, also, to the program manager in choosing a reliability growth model, are what estimation procedures are available and what type of data are required for these models.

Con 4

This paper considers a popular parametric reliability growth model; the so-called Duane Model. Some background on this model will be given along with appropriate estimation and goodness of fit procedures. A discussion of an actual Army application will, also, be given.

2. THE DUANE MODEL

In 1962, J. T. Duane of General Electric Company's Motor and Generator Department (see also Duane [1964]), published a report in which he discusses his observations on the failure data for five divergent types of systems during their development programs at G.E. These systems included complex hydromechanical devices, complex types of aircraft generators and an aircraft jet engine. The study on the failure data was conducted in an effort to determine if any systematic changes in reliability improvement occurred during the development programs for these systems. His analysis revealed that for these systems, the observed cumulative failure rate versus cumulative operating hours fell close to a straight line when plotted on log-log paper. (See Figure 1.) From this study Duane postulated his reliability growth model.

Mathematically, this model may be expressed by the equation

$$C(t) = \lambda t^{-\alpha},$$

$\lambda > 0$, $0 < \alpha < 1$, where $C(t)$ is the cumulative failure rate of the system at time t and λ and α are parameters. By definition $C(t) = F(t)/t$, where $F(t)$ is the expected number of failures experienced by the system during t units of development testing. Therefore,

$$\frac{F(t)}{t} = \lambda t^{-\alpha}$$

or

$$F(t) = \lambda t^{1-\alpha}.$$

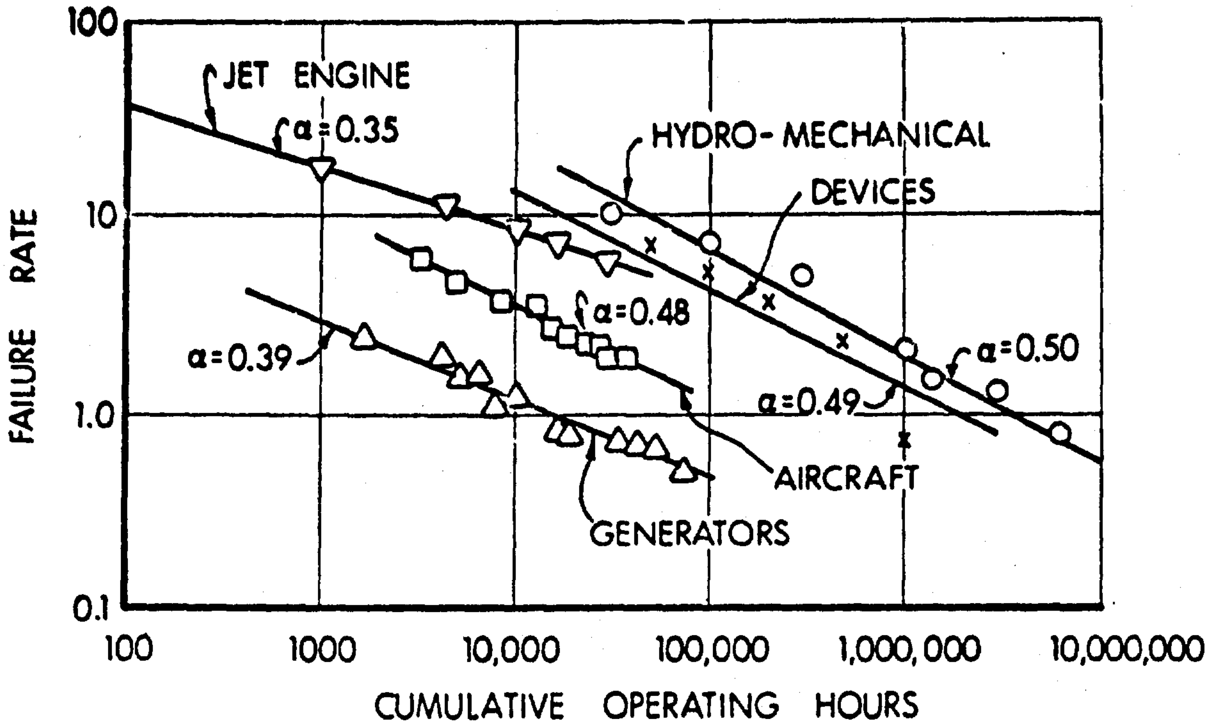


Figure 1. Original Duane Data.

The instantaneous failure rate, r(t), of the system is the change per unit time of F(t), the expected number of failures. This yields,

$$r(t) = \frac{d}{dt} F(t) = \frac{d}{dt} \lambda t^{1-\alpha} = (1-\alpha)\lambda t^{-\alpha}.$$

If we let $\beta = 1 - \alpha$, then r(t) becomes

$$r(t) = \lambda\beta t^{\beta-1}$$

which is recognized as being the Weibull failure rate function for a repairable system. This notation will be used throughout the remainder of the paper.

The Duane model assumes that if development testing is stopped at some time t_o, say, and the system is put into production with the configuration fixed as it was at time t_o, then the failure times of the systems that are produced will follow an exponential distribution with MTBF

$$M(t_o) = \frac{1}{r(t_o)} = \frac{t_o^{1-\beta}}{\lambda\beta}$$

when they are put into service. That is, these systems will have life distribution

$$H(x) = 1 - e^{-x/M(t_o)}$$

$x > 0$. Note that the MTBF

$$M(t) = \frac{1}{r(t)} = \frac{t^{1-\beta}}{\lambda\beta}$$

increases as the development testing time increases (since $\beta < 1$) and is proportional to $t^{1-\beta}$. If $\beta = 1$ then $M(t)$ is equal to a constant for all t. In this case there is no reliability growth. The parameter β then is a growth parameter reflecting the rate in which reliability or MTBF increases with development testing time.

With this notation $\beta = 0.5$ closely represented the types of systems considered by Duane.

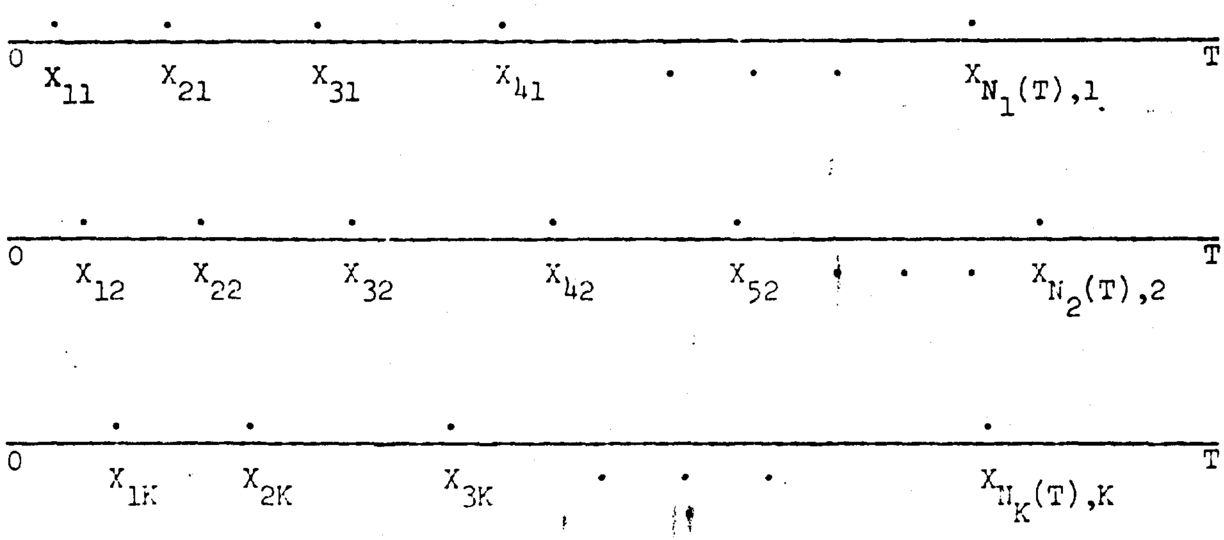
In 1970, J. D. Selby and S. G. Miller, also of G.E., published a paper entitled "Reliability Planning and Management - RPM" which incorporated Duane's reliability growth model into the management aspects of planning and conducting a development program. They mentioned that in addition to the types of equipment considered by Duane in the original study, the model had, also, been confirmed to apply to avionics equipment on four development programs at G.E. It was noted, too, in this paper that a maximum growth rate of $\beta = 0.4$ was estimated, and one which has not been experienced at G.E. However, a growth rate of $\beta = 0.5$ for a well-planned program was not unusual at G.E. and a growth rate of $\beta = 0.9$ was estimated as a minimum.

It is important to note that the RPM approach assumes that the development program is conducted in a test-fix-test-fix manner. That is, the system is tested until a failure occurs. Design and/or engineering modifications are then made as attempts to eliminate the failure mode(s) and the system is tested again. This process is continued until the desired reliability is obtained.

If the program manager knows that the failure rate of a previously developed, similar type system followed the Duane model with a certain λ and β, then he may use this information to plan and manage his development program. It cannot arbitrarily be assumed, however, that the reliability growth of military systems will follow the Duane model. Moreover, if various military systems did follow this model it equally cannot be arbitrarily assumed that they will experience similar growth rates as experienced by G.E. It is important then that failure data on existing military systems under development be analyzed to determine if the Duane model is appropriate. If it is found to be appropriate then the estimates of λ and β can be used to monitor the reliability of the present system under development and, also, to aid in the planning and management of future development programs for similar type systems.

Goodness of fit and estimation procedures will be given next for the Duane model when the data are time truncated. (Other related procedures for this model are given in Crow [1972].) A numerical example illustrating these procedures will be given, followed by a discussion of an Army application of the Duane model.

Suppose K systems have each experienced T units of operation since the development program began. Let $N_r(T)$ be the random number of failures observed for the r-th system, $r = 1,\ldots,K$. Let X_{ir} be the age of the r-th system (regarding the age at the beginning of development as 0) at the i-th failure, $i = 1,\ldots,N_r(T)$, $r = 1,\ldots,K$.



The maximum likelihood estimate (MLE) of β, the growth parameter, is

$$\hat{\beta} = \frac{N}{\sum_{r=1}^{K} \sum_{i=1}^{N_r(T)} \log \frac{T}{X_{ir}}}$$

where

$$N = \sum_{r=1}^{K} N_r(T).$$

The MLE $\hat{\beta}$ is a biased estimate of β. The estimate

$$\bar{\beta} = \frac{N-1}{N} \hat{\beta}$$

is, however, unbiased. The MLE of λ is

$$\hat{\lambda} = \frac{N}{KT^{\hat{\beta}}}.$$

(All logs are with respect to base e.)

The goodness of fit statistic to determine if the Duane model fits the data is calculated as follows. Firstly, treat all the N failure times X_{ir} $i = 1,\ldots,N_r(T)$, $r = 1,\ldots,K$, as one group and order them smallest to the largest. Call these ordered failure times $Z_1, Z_2, \ldots, Z_N$. That is, Z_1 is the smallest X_{ir}, Z_2 is the next smallest $X_{ir}, \ldots, Z_N$ is the largest X_{ir}, $i = 1,\ldots,N_r(T)$, $r = 1,\ldots,K$. Secondly, compute the statistic

$$W_N^2 = \frac{1}{12N} + \sum_{j=1}^{N}\left(\left(\frac{Z_j}{T}\right)^{\bar{\beta}} - \frac{2j-1}{2N}\right)^2 .$$

Observe that $\bar{\beta}$, the unbiased estimate of β, is used in this formula. This statistic is a parametric form of the Cramér-Von Mises statistic and has an asymptotic distribution with mean 0.09259 and variance 0.00435 when the data follow the Duane model.

Critical values for this statistic for N = 2 thru 60 have been calculated at AMSAA from Monte Carlo simulation using 15,000 samples for each value of N. These critical values are given in Table 2. If W_N^2 is greater than the selected critical value then the hypothesis that the Duane model fits the data is rejected at the designated significance level. If W_N^2 is less than this value then the hypothesis that the Duane model fits the data is accepted.

Example

Suppose K = 3 systems were tested for time T = 200. This experiment was simulated on a computer when $\lambda = 0.6$ and $\beta = 0.5$. These results are given in Table 1 where X_{ir} is the age of the r-th system at the i-th failure. From these data the MLE of β is $\hat{\beta} = 0.615$, and the MLE of λ is $\hat{\lambda} = 0.461$.

The unbiased estimate of β is $\bar{\beta} = (35/36)\hat{\beta} = 0.598$.

For the goodness of fit test we next order the X_{ir}'s. This gives $Z_1 = 0.1$, $Z_2 = 4.3$, $Z_3 = 4.4$, $Z_4 = 5.6, \ldots, Z_{35} = 195.8$, $Z_{36} = 197.2$. Using these ordered failure times and $\bar{\beta}$, we calculate

$$W_{36}^2 = 0.069.$$

Table 1

SIMULATED DATA FOR K=3 SYSTEMS OPERATED FOR TIME T=200 WHEN λ=0.6 AND β=0.5

SYS. 1	SYS. 2	SYS. 3
X_{i1}	X_{i2}	X_{i3}
4.3	0.1	8.4
4.4	5.6	32.5
10.2	18.6	44.7
23.5	19.5	48.4
23.8	24.2	50.6
26.4	26.7	73.6
74.0	45.1	98.7
77.1	45.8	112.2
92.1	75.7	129.8
197.2	79.7	136.0
	98.6	195.8
	120.1	
	161.8	
	180.6	
	190.8	

For a hypothesis test at the .05 significance level we find in Table 2 that the corresponding critical value for N = 36 is 0.213. Since 0.06[illegible] is less than 0.213, we accept the hypothesis that the Duane model fits the data.

The Duane model states that if development of the system is stopped at t = 200 hours of testing, then the times between failures of the system thereafter will follow the exponential distribution

$$F(x) = 1-e^{-x/M(t)}$$

$x \geq 0$, where

$$M(t) = [r(t)]^{-1} = \frac{(200)^{1-\beta}}{\lambda\beta}.$$

Based on 200 hours of testing the MLE of M(t) is

$$\hat{M}(200) = \frac{(200)^{1-\hat{\beta}}}{\hat{\lambda}\hat{\beta}} = 27.1[illegible].$$

If development is stopped at, say, t = 300 hours of testing, the model states that future times between failures will, also, follow the exponential distribution but with mean

$$M(300) = \frac{(300)^{1-\beta}}{\lambda\beta}.$$

Based on 200 hours of testing the projection of the MTBF at 300 hours of testing is

$$\hat{M}(300) = \frac{(300)^{1-\hat{\beta}}}{\hat{\lambda}\hat{\beta}} = 31.70.$$

— —

An application of the Duane model to an Army system will be discussed next.

Application 1

A complex, electronic system was analyzed for reliability growth using the Duane model. The first set of data available for analyses was based on 755 hours of development testing. There were 45 failures during this period and the data consisted of the ages of the system when it failed. Figure 2 shows the average failure rates of this system over 100 hour intervals, based on these data.

Using the data the MLE's of λ and β were computed to be $\hat{\lambda}_1 = 0.770$, $\hat{\beta}_1 = 0.614$. The unbiased estimate of β is $\bar{\beta}_1 = 0.600$.

The Cramér-Von Mises goodness of fit statistic was calculated next using the ordered failure times and $\bar{\beta}_1$. It was decided to use a 1% significance level. From Table 2 the corresponding critical value for $N = 45$ is 0.342 and the calculation of the Cramer-Von Mises statistic yielded

$$W^2_{45} = 0.047.$$

Since, $0.047 < 0.342$, the hypothesis that the Duane model fits the data is accepted at the 1% level. Moreover, the small numerical value of W^2_{45} indicates a very good fit.

Using the MLE's of λ and β the MLE of the failure rate function is

$$\hat{r}_1(t) = \hat{\lambda}_1\hat{\beta}_1 t^{\hat{\beta}_1 - 1}.$$

Figure 3 shows graphically this estimated failure rate. The estimated failure rate is projected past 755 hours by the dash line.

The MTBF of the system, as a function of test time, is estimated by

$$\hat{M}_1(t) = [\hat{r}_1(t)]^{-1}.$$

This MTBF curve is shown graphically in Figure 4, where again the dash line is the projection past 755 hours of testing. The estimate of the

current MTBF is given by

$$\hat{M}_1(755) = 27.33.$$

The dash line of Figure 4 gives the estimated increase in MTBF accomplished by further development testing.

Failure data on this system to 1100 hours of testing became available at a later time. Using all the data from 0 to 1100 hours, new, revised estimates of λ and β were obtained. The MLE estimates were $\hat{\lambda}_2 = 0.693$, $\hat{\beta}_2 = 0.634$. After 1100 hours of development testing the estimate of the current MTBF is

$$\hat{M}_2(1100) = [\hat{r}_2(1100)]^{-1}$$

where

$$\hat{r}_2(t) = \hat{\lambda}_2\hat{\beta}_2 t^{\hat{\beta}_2 - 1}.$$

This gives

$$\hat{M}_2(1100) = 29.38.$$

Based on data to 755 hours, the projected MTBF at 1100 hours was

$$\hat{M}_1(1100) = 31.60.$$

This analysis shows that for this complex, electronic system, the failure data apparently followed the Duane model. Similar results have been experienced for other complex, electronic and mechanical systems analyzed in this fashion at AMSAA.

Table 2. Critical Values of W_N^2

SAMPLE SIZE N	Level of Significance				
	.20	.15	.10	.05	.01
2	.139	.150	.161	.175	.186
3	.121	.135	.154	.183	.231
4	.121	.136	.156	.195	.278
5	.123	.138	.160	.202	.305
6	.123	.139	.163	.206	.315
7	.124	.141	.166	.207	.305
8	.124	.141	.165	.209	.312
9	.124	.141	.167	.212	.324
10	.124	.142	.169	.213	.321
11	.124	.142	.166	.216	.324
12	.125	.143	.170	.213	.323
13	.126	.143	.168	.218	.337
14	.126	.142	.169	.213	.331
15	.125	.144	.169	.215	.335
16	.125	.143	.169	.214	.329
17	.126	.143	.169	.216	.334
18	.126	.143	.170	.216	.339
19	.126	.143	.169	.214	.336
20	.127	.145	.169	.217	.342
21	.126	.145	.170	.216	.332
22	.126	.144	.171	.216	.337
23	.127	.144	.169	.217	.343
24	.126	.143	.169	.216	.339
25	.127	.145	.170	.216	.342
26	.127	.145	.171	.215	.333
27	.127	.144	.170	.215	.335
28	.127	.145	.170	.218	.334
29	.127	.146	.171	.217	.334
30	.127	.145	.172	.218	.328
31	.127	.145	.170	.215	.328
32	.127	.145	.169	.214	.330
33	.127	.144	.169	.215	.337
34	.126	.143	.171	.213	.334
35	.127	.144	.170	.215	.326
36	.126	.144	.169	.213	.331
37	.127	.145	.170	.215	.339
38	.127	.145	.170	.217	.331
39	.127	.145	.173	.218	.334
40	.128	.146	.172	.220	.335
41	.128	.146	.173	.218	.335
42	.128	.146	.172	.217	.333
43	.127	.146	.172	.217	.334
44	.128	.147	.173	.218	.341
45	.128	.146	.172	.217	.342
46	.129	.146	.172	.216	.346
47	.128	.147	.173	.216	.343
48	.128	.145	.172	.219	.343
49	.127	.145	.171	.218	.335
50	.127	.145	.172	.219	.345
51	.128	.146	.173	.220	.344
52	.127	.146	.172	.216	.346
53	.127	.146	.172	.218	.348
54	.127	.146	.172	.219	.351
55	.127	.145	.173	.219	.356
56	.127	.145	.172	.221	.355
57	.127	.145	.171	.218	.352
58	.127	.145	.171	.221	.353
59	.128	.146	.171	.222	.350
60	.127	.146	.172	.219	.352

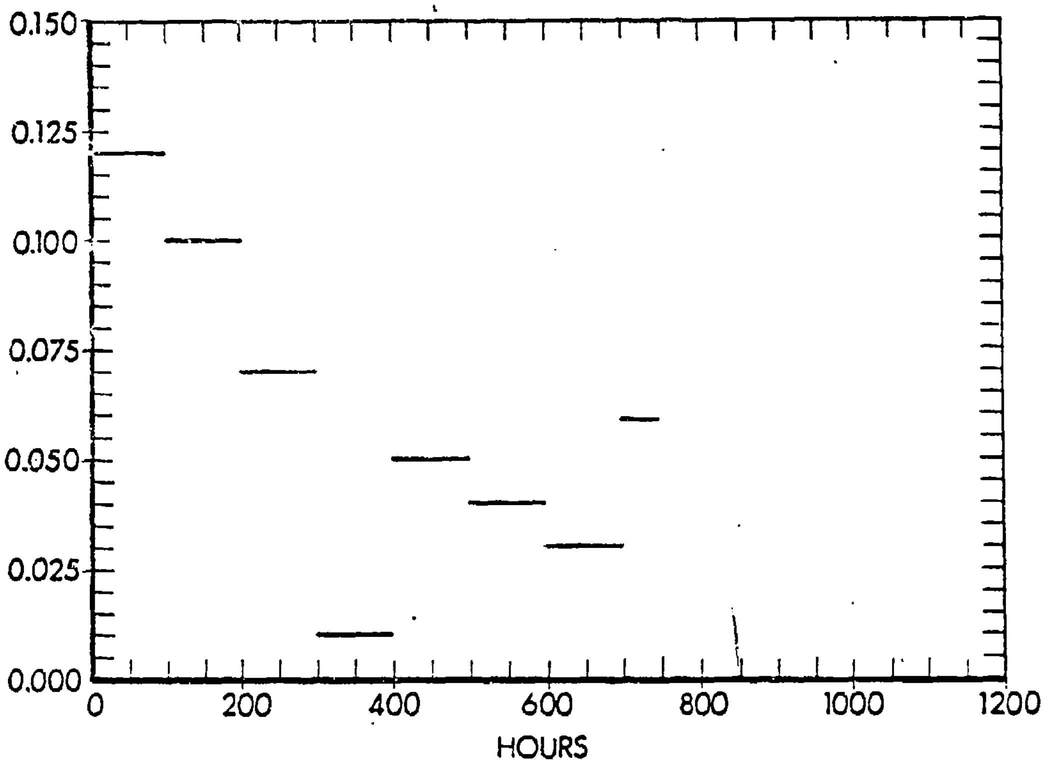


Figure 2. Average Failure Rate.

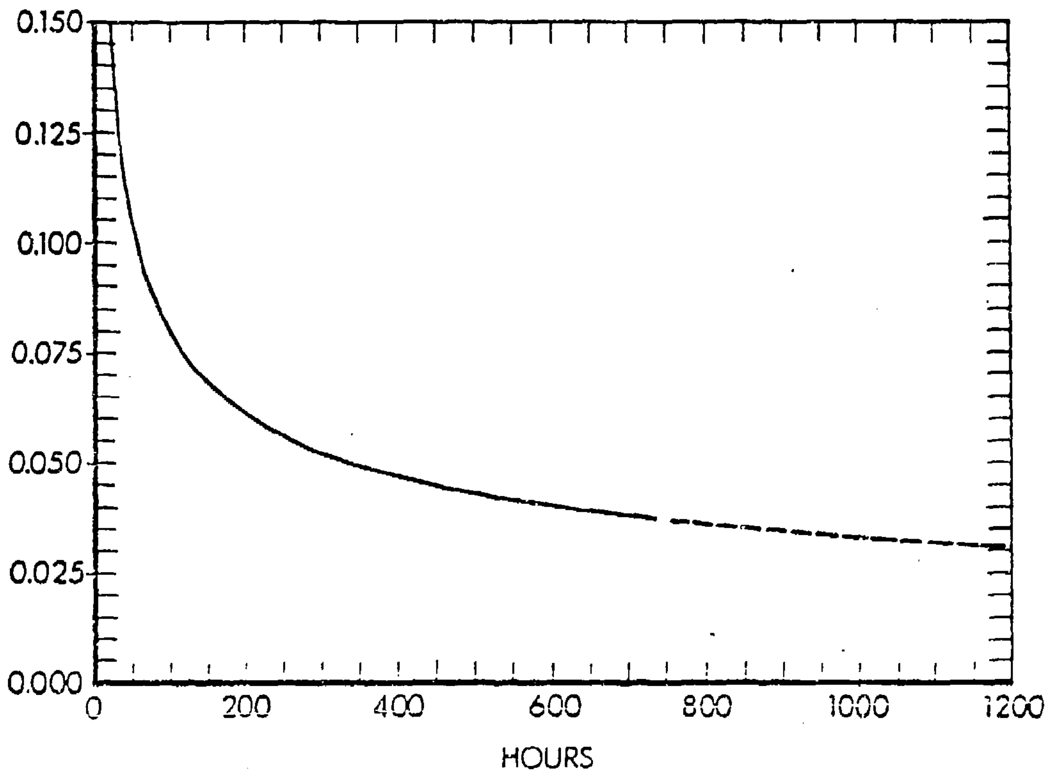


Figure 3. Estimated Failure Rate.

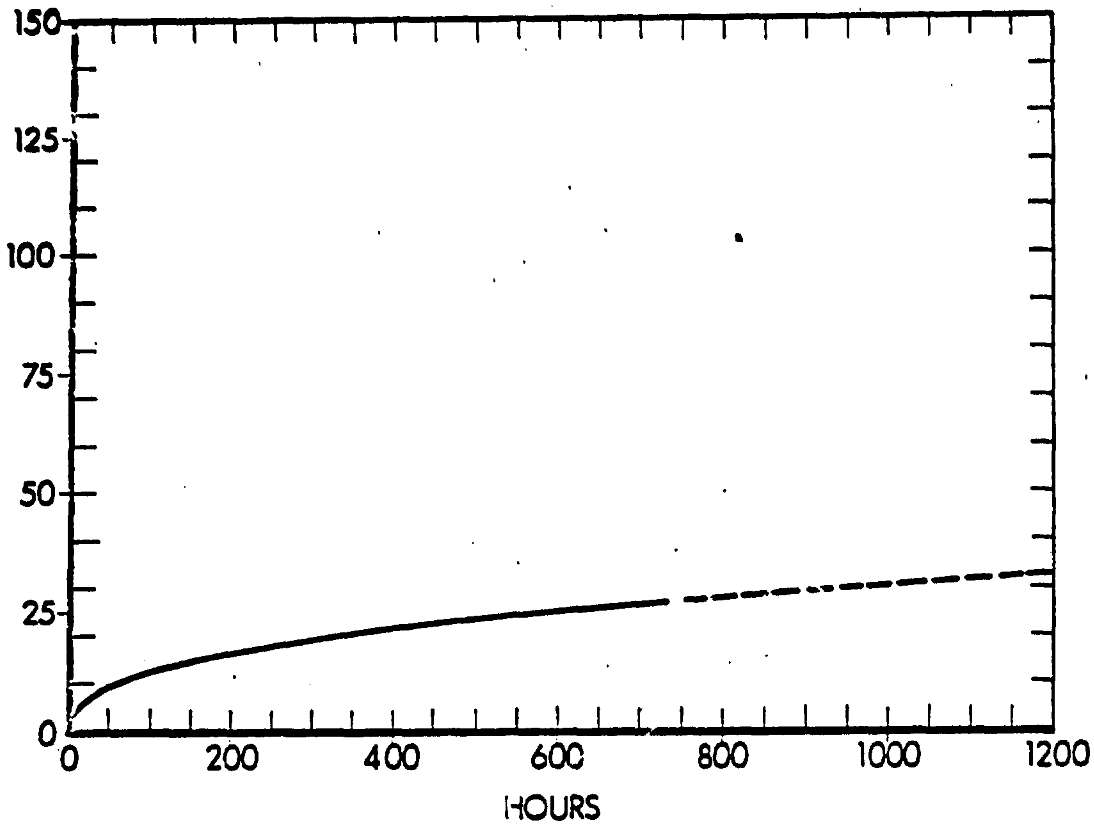


Figure 4. Estimated MTBF.

ACKNOWLEDGMENTS

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MASS CORE MEMORY UNIT DECISION RISK ANALYSIS

Mr. David A. Tyburski

US Army Electronics Command

1. Objective

The objective of this study is to evaluate the cost, scheduling and technical risks involved in replacing the present TACFIRE Memory Banks and the Random Access Memory with an all solid state Mass Core Memory to be developed by a contractor.

2. Background

The contractor prepared an unsolicited proposal for the Project Manager to develop a Mass Core Memory Unit (MCMU) to replace the present memory system in TACFIRE.

The Project Manager requested that the Systems Analysis Division, Plans and Analysis Directorate, perform a Decision Risk Analysis to study the feasibility of accepting this proposal as a product improvement for TACFIRE.

This task was assigned on a quick reaction basis to be completed in three weeks.

The proposal cited the following advantages or improvements to TACFIRE:

a. Reduced power requirements from 750 watts to 502 watts at Battalion;

b. Significant space reduction in the shelters;

c. Weight reduction from 550 lbs. to 250 lbs. at Battalion.

d. Better center of gravity in the shelters.

e. Increased reliability.

f. Increased memory storage capacity.

g. Decreased response times for fire missions under load by 5-13 percent.

3. Alternatives

With respect to the proposed product improvement, there are two basic choices. These are to either reject the proposal or accept the proposal and fund the MCMU development. However, if the choice is made to accept the proposal then there are several ways to phase the MCMU into the production schedule of TACFIRE. The alternatives which were selected for consideration in this analysis are listed below.

a. Alternative A - Reject the proposal and continue with the present TACFIRE development.

b. Alternative B - Accept the proposal and slip the first Production-go-Ahead (PGA) to be concurrent with completion of the development tasks stated in the proposal.

c. Alternative C - Accept the proposal and do not slip the first PGA but initiate a Production Design Change at the time of completion of development tasks necessary to make subsequent production-go-ahead decisions.

The RISCA networking model was used to evaluate schedule and cost risks for the alternatives considered. Figure 1 depicts the macro-flow chart for the network employed for this analysis which is the development activities provided by the contractor for the development for the MCMU and the schedule of activities for TACFIRE including the first PGA.

This network was used to obtain distributions of time and cost for the development of the MCMU and the time to the TACFIRE first PGA and second PGA. It was also used to determine probabilities of the MCMU development meeting certain required TACFIRE milestones. An assumption was made that the MCMU development and TACFIRE ET/EST will begin concurrently.

Estimates of time for development of the MCMU are based on the contractor's estimates of the most likely time. Ten percent below the most likely time represents the optimistic estimates, and 30% above the most likely times indicates pessimistic estimates. The point in time on the contractor schedule chosen for the decision point for development of the MCMU is the PSS demonstration. It is at this point that a functional equivalent of the end item will be demonstrated.

4. Cost and Schedule Risks.

Alternative A assumed continuing with the present TACFIRE development schedule. This schedule is assumed to be low risk since the TACFIRE equipment has been developed and is about to complete Research and Development Acceptance Tests (RDAT). Uncertainty is involved in meeting the first production-go-ahead. This milestone is critical since any slippage of this date results in a penalty to the government of 110 thousand dollars per week of slippage up to a maximum of 12 weeks.

Using the RISCA model the distribution of time expected for the end of ET/EST was determined. A worst case of two months slippage was used for this analysis. This estimate was obtained from the Project Manager. The expected time of completion of ET/EST is 54.7 weeks and the expected slippage cost is 175 thousand dollars. The 90% confidence level for time is 57.3 weeks and for cost it is 365 thousand dollars.

Alternative B assumes slippage of the present TACFIRE schedule until completion of the MCMU development. The risk to meeting the present TACFIRE schedule under this alternative is high. The probability of meeting the first PGA is zero.

Figure 2 illustrates the probability of developing the MCMU for any given number of weeks and the slippage penalty up to twelve weeks of slippage that would be incurred if the first PGA were slipped. The dotted line represents the probability of developing the MCMU and the solid line represents the slippage penalties incurred as a function of time. The

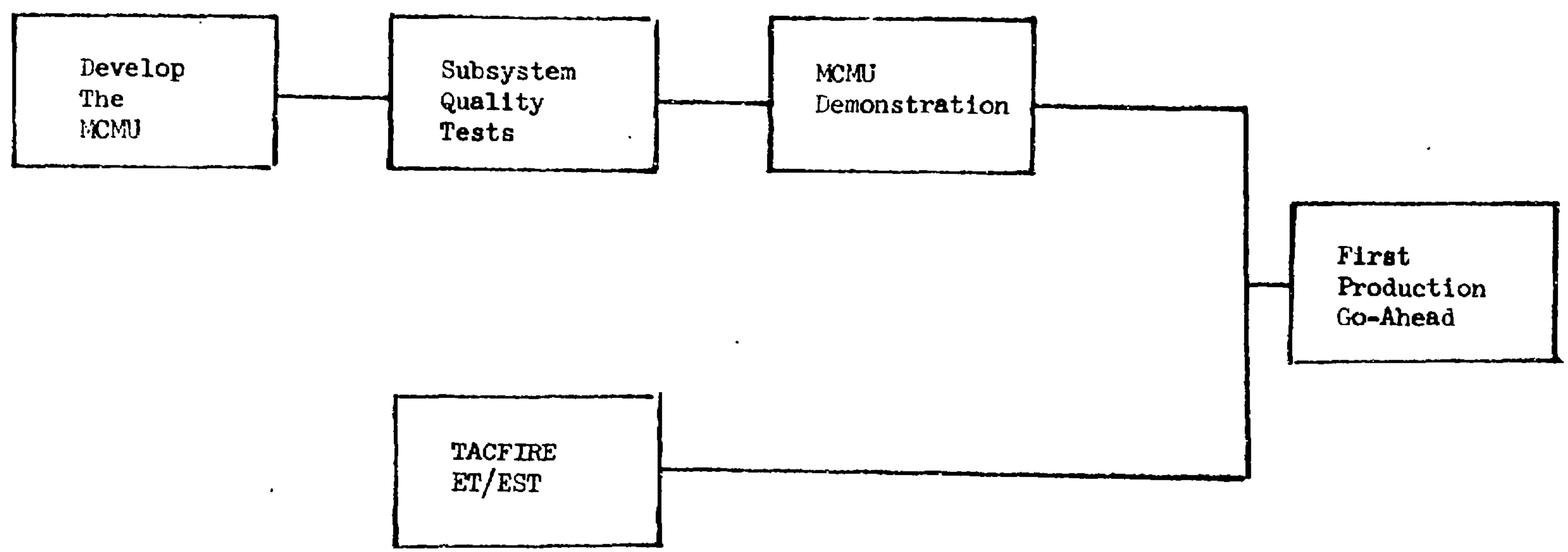

Figure 1 MCMU Development Macro-Flowchart

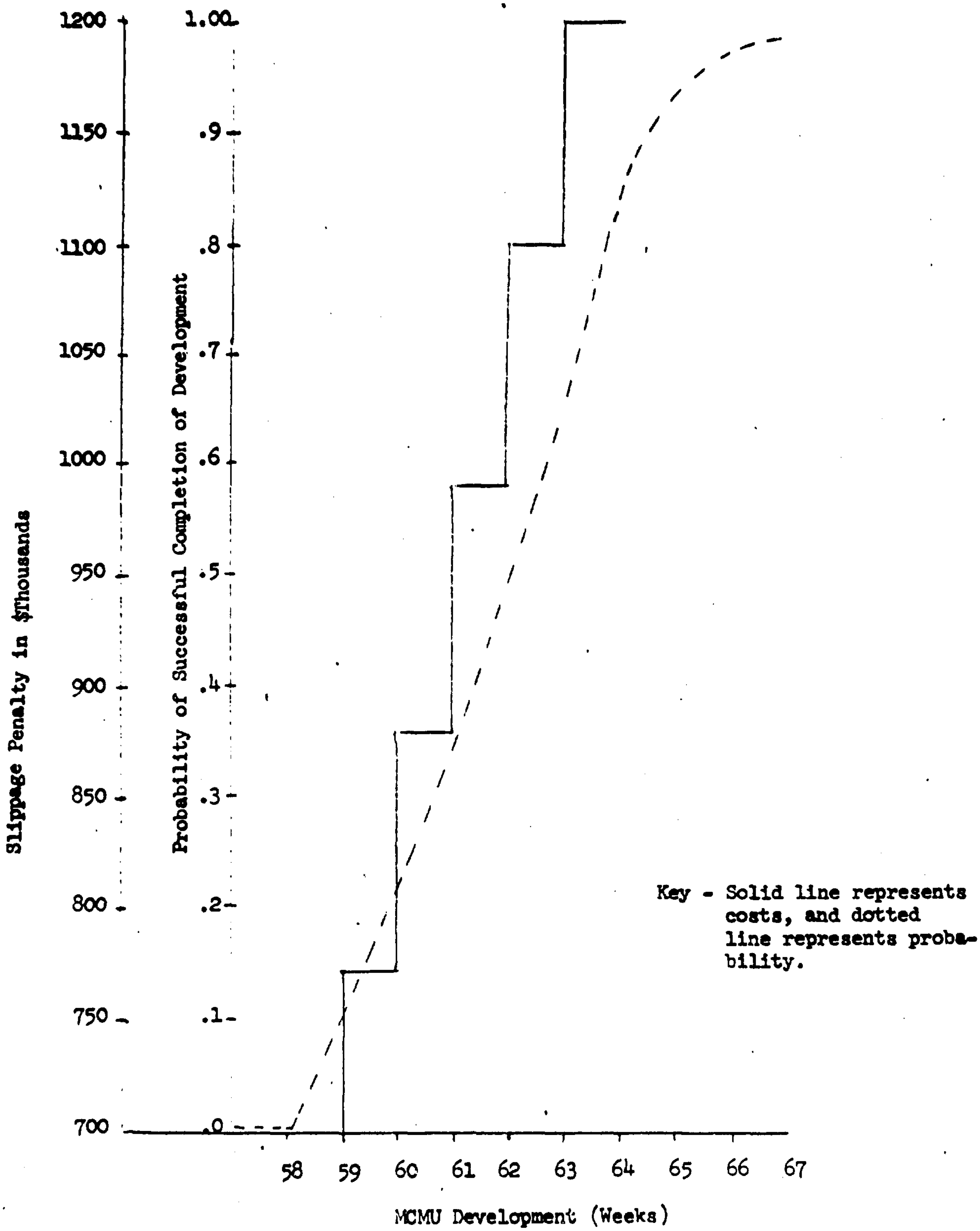

Figure 2 Slippage Penalty and Probability of Successful Completion of Development vs. Development Time

graph illustrates that for a confidence level of 84% of completing the MCMU development the PGA will slip 12 weeks at a cost to the government of 1.2 million dollars. Figure 2 also indicates that there is a 15 percent probability that the MCMU development will require more than twelve weeks of slippage.

Alternative C assumes the continuation of the present TACFIRE development schedule with the MCMU phased into the development schedule when it is available. This alternative provides the least risk to the present TACFIRE schedule, since it assumes no slippage in the present schedule. The probability of development of the MCMU before the first PGA is zero based on analysis of Alternative B, therefore, the next point in time at which the MCMU could be phased into the program is the second PGA. It was determined that the probability of completing the MCMU by the second PGA was almost 100 percent.

This indicates that relative to the development schedule, the MCMU would be available to be phased in at the second PGA. Units produced under the first PGA would have to be retrofitted. The Project Manager estimated that roughly 3 million dollars worth of present memory equipment would have to be removed from retrofitted equipment.

5. Life Cycle Costs

The cost per bit estimated for the MCMU is 1.1 cent per bit. The present TACFIRE militarized core costs about 12 cents per bit. The militarized core used in the Navy VYK-7 is estimated at 10 cents per bit. The contractor bases their estimate of no increase in production costs for the MCMU on the 1.1 cent per bit estimate for core. There is risk involved in the low cost per bit quoted by the contractor since past experience indicates that militarized core has cost as much as 10 times what the contractor has quoted.

Since the MCMU development schedule does have risk associated with it and since the development is to be a cost plus fixed fee contract, it could be estimated that the 2.8 million dollars for the MCMU contract could be as high as 3.6 million dollars assuming a 30% overrun in schedule.

The contractor estimates a life cycle cost savings of 12. million dollars in maintenance and logistics cost due to the higher reliability of the proposed MCMU and due to the fact that drum memories which must be repaired at depot level will not be used in the MCMU.

The major cost savings specified by the contractor occur in the categories of depot labor and repairables required at the depot level. A savings of 480 thousand dollars is specified for transportation of drum memories from the field to the depot where they are sent for repair.

There was not enough time available during this analysis to verify life cycle cost estimates made by the contractor. A cursory estimate of drum transportation costs was made and it indicated that life cycle drum transportation costs were of an order of magnitude of 24-50 thousand dollars.

6. Technical Risk

The technical risks for Alternatives B and C are identical since both

alternatives assume development of the MCMU with the Litton development schedule.

Estimates of technical risks involved in the MCMU development were obtained from the technical laboratories. The degree of overlap necessary in the MCMU development schedule could lead to serious technical problems. The value of building stages of hardware models is to learn by experience and provide corrections to subsequent models. The amount of parallelism in the MCMU schedule precludes the possibility of such feedback.

If the present schedule for development of the MCMU is adhered to, the technical feedback necessary from breadboard model to engineering model, to preparation model is not available. The probability of developed items meeting specifications under such a development program is very low.

The data reliability or error rate required for the MCMU is one error in 10^{12} bits accessed. An error rate of this quality in a memory of the size of the MCMU is only obtainable by experience and careful attention to manufacturing detail. The schedule presented by the contractor has the effect that little information can be obtained from successive models and solutions to problems tend to be "quick-fix". The lack of feedback and the use of "quick-fixes" are expected to degrade the expected error rate. It is therefore expected that the error bit rate of one error in 10^{12} bits accessed will not be achieved under the contractor's development schedule.

The contractor predicts a 3760 mean time between failure (MTBF) for the MCMU. Similarly, the contractor predicts an increase in MTBF at Battalion level of 860 hours and at Div Arty level an increase of 30 hours. The government predicts an increase at Battalion level of 300 hours and a decrease at Div Arty level of 250 hours MTBF.

7. Sensitivity of Alternatives to MCMU Development

Alternatives B and C will have different impacts on cost and schedule risks if the MCMU development is not successful. For Alternative B if the MCMU development is funded but a determination can be made prior to the first PGA that the development will not be successful, the present TACFIRE schedule may be adhered to and the dollar loss would be all or a portion of the development cost of the MCMU. If, under Alternative B, the determination that the MCMU development will not be successful is made after the first PGA is slipped, the dollar loss will be for the development of the MCMU and for slippage penalty costs incurred because of slippage of the first PGA. Also the TACFIRE production schedule will have slipped an amount of time equal to the time after the first PGA when the determination of failure of the MCMU development is made.

For Alternative C, if the MCMU development fails, there is no slippage of the present TACFIRE schedule. This is because the TACFIRE development and the MCMU development are parallel independent activities. The dollar loss that would be incurred would be for the development of the MCMU.

8. Tradeoff Analyses

There are two areas in which tradeoffs must be considered. The first is the tradeoff of product improvement to the TACFIRE system through acceptance of

the proposal versus the costs incurred by accepting the proposal. The second area of tradeoff exists in the area of phasing the MCMU into the TACFIRE production schedule if the proposal is accepted.

The significant product improvements which will be obtained without risk by accepting the proposal are the reduction of weight from 550 lbs to 250 lbs at Battalion and the space reduction within the shelters. The reduction in mission response time is desired but the present TACFIRE system response times are already below the requirements for the system. The increase in reliability to be obtained with the MCMU is also desirable but the technical risks involved in the development of the MCMU casts doubt on the accuracy of these predictions. Also the reliability predictions made by the government indicate that the increase in MTBF due to the MCMU may not be as great as those predicated by the contractor.

If the MCMU development is funded there are tradeoffs to be made concerning when to phase the development into the TACFIRE production schedule The tradeoff to be made involves Alternatives B and C. Alternative B involves a high risk to the TACFIRE schedule since the first PGA is slipped until the MCMU development is completed. Alternative C involves a low risk to scheduling since the MCMU is to be phased into the TACFIRE schedule, most likely at the second PGA, without slipping the first PGA. Of course, TACFIRE systems produced under the first PGA must be retrofitted with the new memory systems when they are available.

There are cost risks for both alternatives. For Alternative B, slippage penalty costs are 110 thousand dollars per week for the first twelve weeks and after twelve weeks the government is liable for all damages incurred by the contractor due to slippage of the first PGA beyond the first twelve weeks.

For Alternative C the costs involved are those to produce the present drum memory system under the first PGA. These systems would be removed from the TACFIRE system when the MCMU became available. This cost is estimated to be 3 million dollars.

In summary, Alternative B will cause slippage of the entire TACFIRE schedule. The cost to the government of this alternative is expected to be 1.2 million dollars but this is not the maximum cost. The maximum costs are all damages incurred by the contractor after the first twelve weeks of slippage. Alternative C involves no schedule risk to the present TACFIRE schedule. The cost risk is limited to the cost of memory equipment produced under the present production schedule which must be replaced when the MCMU became available. Also under Alternative C, if the MCMU development is not successful, the present system will be available for issue to the troops.

9. Results and Recommendations

The cost and schedule risks are listed in Table I for Alternatives A, B and C. These estimates are based on information derived from the RISCA model runs assuming the contractor development schedule.

Based on the evaluation of the proposal, the technical risks involved in a new development of this type with the development schedule proposed by the contractor indicate that the data reliability or error rate for the MCMU will be less than that specified by Litton. The mean-time-between-failure of the

TABLE I

ALTERNATIVE	SCHEDULE SLIPPAGE PAST FIRST PGA	COST (Millions of Dollars)
A	50% confidence level of less than 2.7 weeks	Slippage Cost .175
B	50% confidence level of less than 11.4 weeks	Slippage Cost 1.2 + Development Cost
	84% confidence level of less than 12 weeks	Slippage Cost 1.2 + Development Cost
	100% confidence level of less than 15 weeks	Slippage Cost 1.2 + Development + All Damages to Litton
C	Same for Alternative A	Development Cost + $3.0 of Present Memory Equipment

SAM-D FIRING DOCTRINE MODEL

Major Ernest R. Jackson
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INTRODUCTION

This presentation is to describe a SAM-D Firing Doctrine simulation model and how it will be used to evaluate the SAM-D system effectiveness. The model will be used to evaluate the effectiveness of various firing doctrine alternatives as well as the effectiveness of a specific firing doctrine against the different threats which the SAM-D system could encounter.

In order to help understand this SAM-D Firing Doctrine Model, I will provide a brief review of the development of the SAM-D system along with an overall system description.

The continuing advance of aircraft technology has led to tactical military sircraft which, when equipped with modern defense penetration aids such as responsive electronic countermeasures equipment (jammers), have the capability to either evade or seriously nullify the effectiveness of currently deployed air defense systems. Since the early 1960's there has been a series of efforts aimed at defining the Army's air defense needs for the 1970 era. These efforts have been performed in four major phases:

1. Concept Formulation - which (a) defined the performance characteristics required, (b) formulated and examined the technical feasibility and operational suitability of capable systems, and (c) established the best alternative air defense system from these candidate concepts. In 1966, the Surface-to-Air Missile Development (SAM-D) was established as being the best alternative air defense system.

2. Advanced Development - Initiated by contract with the Raytheon Company in 1967, this development phase served to demonstrate maturity of the technology necessary for mechanizing the unique features of the SAM-D system. The phase was completed in 1971.

3. Engineering Development Definition - Begun in 1970 and completed in 1971, this program phase resulted in (a) detailed definition of the SAM-D system to be developed, (b) a complete plan for the Engineering Development phase, and (c) budgetary estimates of future production and 10 year operating costs.

4. Engineering Development - Started by contract with Raytheon Company in March 1972, the objective of this program phase is to demonstrate, via the development and test of a production prototype system, that the specified levels of performance, effectiveness, and field suitability can be achieved and that the investment and operating costs are within acceptable budget limitations.

MCMU is also expected to be less than that specified.

Technical risks involved in rejecting the Litton proposal are as follows. No weight reduction to the TACFIRE system and no decrease in mission response times will result. Also there is the risk that if expanded capability of the memory system for TACFIRE is required at a future date, this capability for expansion will not be available with the present memory system.

Based on the cost, schedule and technical risks evaluated it was decided by the Project Manager not to accept the MCMU proposal for TACFIRE at this time.

SUMMARY SYSTEM DESCRIPTION

The SAM-D System consists of two operational control elements: the Fire Section, and the Battalion Command/Coordination element. The combat element of the System is the Fire Section which is defined as the minimum complement of equipment and personnel capable of conducting air defense operations. The Fire Section performs all functions and operations associated with the immediate conduct of the air battle, subject to rules of engagement and operating procedures established by the Battalion Commander. Six Fire Sections constitute a SAM-D Air Defense Battalion.

Control over and coordination of Fire Section operations is exercised by the Battalion Commander via a Command/Coordination Unit, which also serves as the link between the SAM-D System and higher air defense authority. Communications between the Battalion/Command Coordination Unit and the Fire Sections, with higher air defense echelons, and between Fire Sections is effected via Communications Relay Units integral to SAM-D.

The significant features which distinguish the SAM-D System from currently deployed air defense systems, and which are fundamental to overcoming the limitations and weaknesses in currently deployed air defense systems, are as follows:

Radar - a single multifunction phased array radar performs the search, target track and missile guidance support functions within the Fire Section. Compared to HAWK and NIKE/Hercules which have 4 and 5 different radars, respectively, per battery, SAM-D has fewer major elements, therefore, requiring considerably fewer operating and maintenance personnel.

Data Processing - all routine and pre-programmable equipment control and engagement control functions are performed by a data processing and control subsystem, which is comprised of a high speed digital computer and appropriate software programs. This feature affords a marked increase in traffic handling acity, when compared to HAWK and NIKE/Hercules. It also permits t ire Section to perform the Fire Control function, thereby eliminating the need for a Battery Control Center and providing a large reduction in the number of operator personnel.

Missile Guidance - command plus dual-mode target via missile (TVM) guidance on a time shared basis between missiles affords the capability to conduct simultaneous engagements while at the same time providing effectiveness against multiple maneuvering targets attacking under the cover of severe electronic countermeasures. Compared to HAWK and NIKE/Hercules, SAM-D has a 4 to 1 advantage in simultaneous engagement capability which, when coupled with the sustained intercept performance and effectiveness, affords the capability to effectively counter repeated attacks.

Subsystem Designs - The hardware subsystem designs are based on the use of standardized digital and analog modules, and reduce the number of

types of peculiar repair parts needed to maintain and support the system.

FIRE SECTION DESCRIPTION

The Fire Section is comprised of one Radar Unit, one Weapon Control Unit, and several Launcher Units, each with four Missile Rounds. Each Missile Round consists of a Missile and a Canister, which serves as a shipping/storage container and launch tube for the Missile.

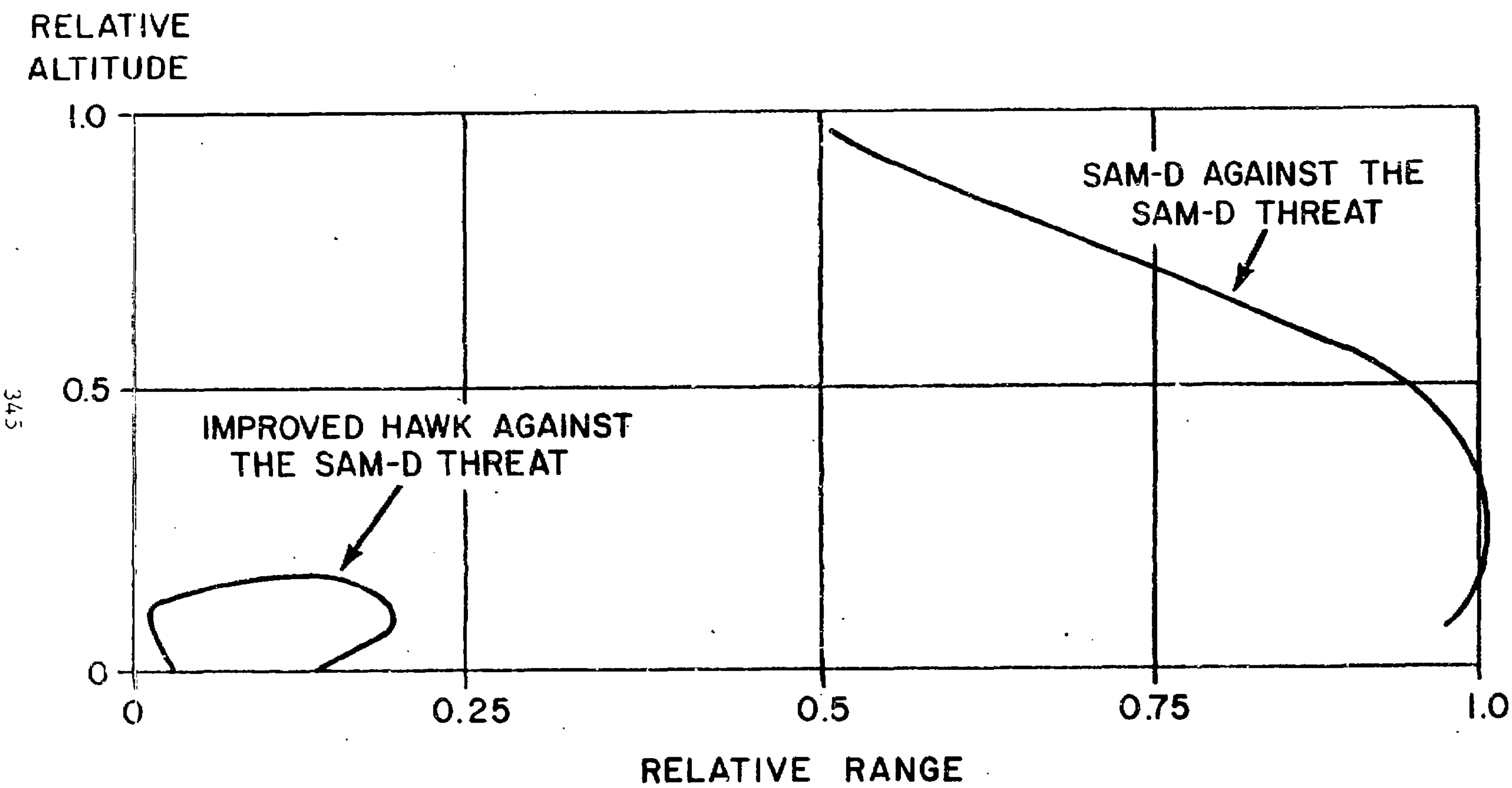
The Radar Unit and Weapon Control Unit, when emplaced with appropriate operational software and software data base, constitute a Fire Control Group. The Fire Control Group performs (within its assigned air space coverage) the air defense functions of search for targets, track on detected targets, and identification and threat assessment on all targets placed under track. Targets adjudged as hostile and within the intercept zone of the Fire Section will be tagged by the Fire Control Group for engagement. The decision to initiate engagement operations may be made by the Fire Control Group when the firing doctrine and operating procedures previously established by the Battalion Commander so permit. In the absence of such permission, engagement operations will be initiated only when and as directed by the Battalion Commander via the Battalion Command/Coordination Unit. Given a decision to engage, the Fire Control Group selects an appropriate Launcher Unit, prepares the necessary launch data, and transmits the launch order and data to the selected Launcher Unit. Upon receipt of a launch order, the Launcher Unit selects and activates the Missile Round as directed. Following selection and activation, missile launch is effected automatically.

Following launch, the Missile is acquired in flight by the Fire Control Group and is then guided to intercept, using the Radar Unit to receive target data from the Missile and to transmit guidance commands to the Missile. These commands are computed in the Weapon Control Unit, using target and Missile data obtained via the Radar Unit.

FIRE SECTION PERFORMANCE

A significant measure of air defense system performance is the range/altitude envelope within which intercepts can be successfully accomplished under given conditions of target characteristics and the operating environment. The accompanying illustration compares the first intercept range/altitude boundaries of the SAM-D and Improved HAWK Fire Sections, assuming expected electronic countermeasures, environmental conditions and target attack tactics in the 1980's and beyond. Although no definitive range or altitude data is shown, suffice it to say that the Improved HAWK first intercept envelop is barely adequate for self-defense in the ECM environment specified for SAM-D. Furthermore, only a single intercept can be achieved within the portrayed intercept envelope. The Improved HAWK Fire Section is incapable of providing credible air defense for Field Army forces under the typical attack conditions expected in the post 1980 era.

INTERCEPT ZONE COMPARISON FOR ECM ENVIRONMENT



The SAM-D first intercept contour occurs at ranges and altitudes three to four times those of the HAWK Fire Section. More importantly, the SAM-D Fire Section can achieve multiple intercepts simultaneously, up to its maximum capability, anywhere on the perimeter of this intercept contour and, in addition, can achieve two more salvos of intercepts before the target penetrates to the minimum intercept range of the Fire Section. Hence, the SAM-D Fire Section can provide credible air defense for Field Army forces against determined attacks, being limited in the case of sustained attacks only by the number of ready missiles available within the Fire Section.

Studies of SAM-D System performance under expected typical sustained attacks against deployed Field Army forces and supporting installations have shown that in a period as short as three days, a single SAM-D Battalion can prevent the destruction of friendly forces valued at five to ten times the life cycle costs of the Battalion.

Although the azimuth angular coverage of the SAM-D Fire Section is only one third that of a HAWK Battery, this has been shown to be of little tactical significance in typical operating terrain, due to hills and other obstructions normally present. In fact, only the best operational sites in Europe provide useable azimuth coverage equal to the coverage of the SAM-D Fire Section.

Clearly, SAM-D offers a credible air defense posture for deployed friendly forces and at a favorable cost/effectiveness ratio.

FIRING DOCTRINE (FIDOC)

Before the SAM-D Firing Doctrine functions can be executed in the system software, a data base must be established in the Weapon Control Computer which contains the necessary target data. This data is provided by the Track Initiation and Tracking function which includes the process of initiating the tracking actions required to establish and maintain or drop a target track. Once a new track has been established in the data base, the firing doctrine functions will be executed on that particular track to determine what actions, if any, should be taken with regard to that track.

The SAM-D Firing Doctrine has been defined to include the following functions:

1. Target Classification - the analysis of radar observables to discriminate targets by type.

2. Target Identification - determination of whether each track is hostile, friendly, or unknown.

3. Target Evaluation - determination of the threat presented by hostile or unknown targets.

4. Weapon Assignment - determination of whether a target is to be engaged and the sequence in which targets should be engaged.

5. Intercept Analysis - receipt of the missile-away message from the launcher, delivery of the missile to the target, and detonation of the missile warhead.

6. Kill Assessment - determination of the target status after warhead detonation.

Real-time algorithms must be developed to perform each of these functions in a satisfactory manner regardless of the particular real-time system status (deployment, available missiles, defended areas, threat tactics). The quality of these algorithms will have a significant impact on the performance of the SAM-D system. Hence, their evaluation and optimization is an important aspect of the overall evaluation and optimization of the SAM-D system. Several subsystem evaluation tools are valuable in aiding the design and evaluation of these algorithms. For efficiency, each evaluation tool should concentrate on one or more aspects of the system while utilizing simple models for other system aspects having only moderate interactions.

There is a grouping of the firing doctrine (FIDOC) functions into four subsets, each benefiting from a specialized evaluation tool: (1) the radar functions (track initiation and tracking); (2) the classification and identification functions (Items 1 and 2); (3) the missile allocation functions (Items 3 and 4); (4) and the Missile functions (Items 5 and 6). An evaluation tool for studying the radar functions requires accurate models of the radar, the environment (including such effects as weather and possible enemy countermeasures), and the threat characteristics affecting radar returns. But it does not require accurate models of other system elements such as the missile. An evaluation tool to study the missile allocation functions requires accurate models of such items as the threat trajectories and attack tactics, the fire section deployment, the defended areas, and the available missiles, with simple models of the radar and the missile itself being adequate. Study of the missile functions requires a one-on-one engagement model which includes an accurate model of the missile dynamics, the warhead, and the target vulnerability, but a detailed (pulse by pulse) radar model is not needed. The classification and identification functions are in a special category because they require analysis of the operating procedures of friendly aircraft as well as analysis of special equipment supporting this function alone.

A number of specialized evaluation tools of various kinds are already available for study of the SAM-D radar functions and the missile functions. There is, however, no specialized evaluation tool (model) currently available to aid development of the missile allocation functions. These functions are difficult to analyze since they are greatly affected by the fire section deployment and by the enemy tactics--both of which are highly variable. Accordingly, there is a need for a very efficient specialized tool allowing the FIDOC designer to test proposed missile allocation policies for a variety of possible deployments and enemy tactics. This

presentation is concerned both with the description of a computer model for evaluating SAM-D firing doctrines and with the use of the model to test and evaluate alternative firing doctrines.

The SAM-D Firing Doctrine Model will incorporate detailed descriptions of the SAM-D fire section deployment, the defended areas, the availability of missiles for launching, and the enemy vehicle trajectories. It will employ (for simplicity and efficiency) simple functional descriptions of the radar and the missile. The model can be used to perform parametric studies of the effects of different performance levels for the FIDOC functions that are modeled in detail (for example, the effects of altering the threat evaluation or the weapon assignment algorithms). The proposed SAM-D Firing Doctrine Model is described in the following section.

SAM-D FIDOC MODEL

Systems Control, Inc. (SCI) is under contract to the US Army Missile Command to develop a SAM-D FIDOC Model. This model is required to help determine the effectiveness of alternate SAM-D firing doctrine policies and hence identify those policies that should be implemented in the system software and Standard Operating Procedures (SOP). It is necessary to evaluate these alternate firing doctrine alternatives to determine their effect on overall system performance. A computerized Tactical Air Defense (TAD) engagement model is required to perform these evaluations. A properly structured engagement model will compute system level indices of performance such as: (i) the expected number of targets killed, (ii) the expected value of surviving assets, and (iii) the expected number of SAM-D missiles employed. The model must be able to perform these computations for a wide variety of threat scenarios, defense deployments, and firing doctrine policies. The model must also be efficient in order to allow the user to perform an adequate number of parametric studies. These studies are needed to determine the strengths and weaknesses of alternate firing doctrine policies when employed in different tactical situations, and to identify firing doctrine policies that consistently yield superior overall TAD system performance.

There are two fundamentally different ways that a TAD engagement model can be implemented in order to account for the randomness of a TAD engagement--by a repetitive Monte Carlo simulation or by forward propagation of the engagement statistics. Whenever a random event must be modeled in a Monte Carlo simulation a random number is chosen and, on the basis of the value of the number, it is decided whether or not the event did occur in that run of the simulation. One run of a Monte Carlo simulation steps through the entire time period of the scenario and models one possible set of outcomes. In order to obtain the statistics of the possible outcomes many runs of the simulation are needed. Thus, the Monte Carlo approach has the virtue of being straight-forward but the drawback of requiring a considerable amount of computation when statistics of the outcome are needed.

An alternative engagement modeling approach is Statistical Engagement Modeling. This type of model steps through the engagement in time increments and, at each time, updates the statistics of the engagement according to the random events that could have occurred during the time interval between updates. The statistics of the engagement at a given time reflect the status of the engagement at that time as could be generated by employing the outcomes of many Monte Carlo runs up to that time. Thus, one pass through an engagement with a statistical engagement model is equivalent to many runs of a Monte Carlo engagement model.

Two difficulties limit the application of statistical engagement models. First, the dimensionality of the statistics may become very large for a high dimensional problem. Second, generation of the equations for computing the statistics can become excessively complex when a very detailed modeling of the system components and their operation is required.

Sometimes the most effective evaluation procedure is to employ a model which combines the statistical and Monte Carlo approaches. The statistical approach is employed for computational efficiency wherever the complexity and dimensionality of the system permits. When the required statistical equations are excessively complex or the dimensionality of the statistics excessively high, the Monte Carlo approach is employed. Thus, a single model is constructed which blends the two modeling techniques.

The basic structure of the SAM-D FIDOC Model is shown in Figure 2. The model is an event sequenced simulation which keys itself to specific significant events which have been identified as critical during the detection, tracking, and engagement process. The details regarding these events and how they are used in the model will be discussed later in this presentation. First it is necessary to understand the inputs to the model and how the simulation is initialized.

INPUTS TO THE SAM-D FIDOC MODEL

The format of inputs and outputs of the SAM-D FIDOC Model is largely a matter of user preference. However, it is useful, in aiding the reader to understand what the model can and cannot do, to briefly describe the types of input required by the model and the types of output it generates.

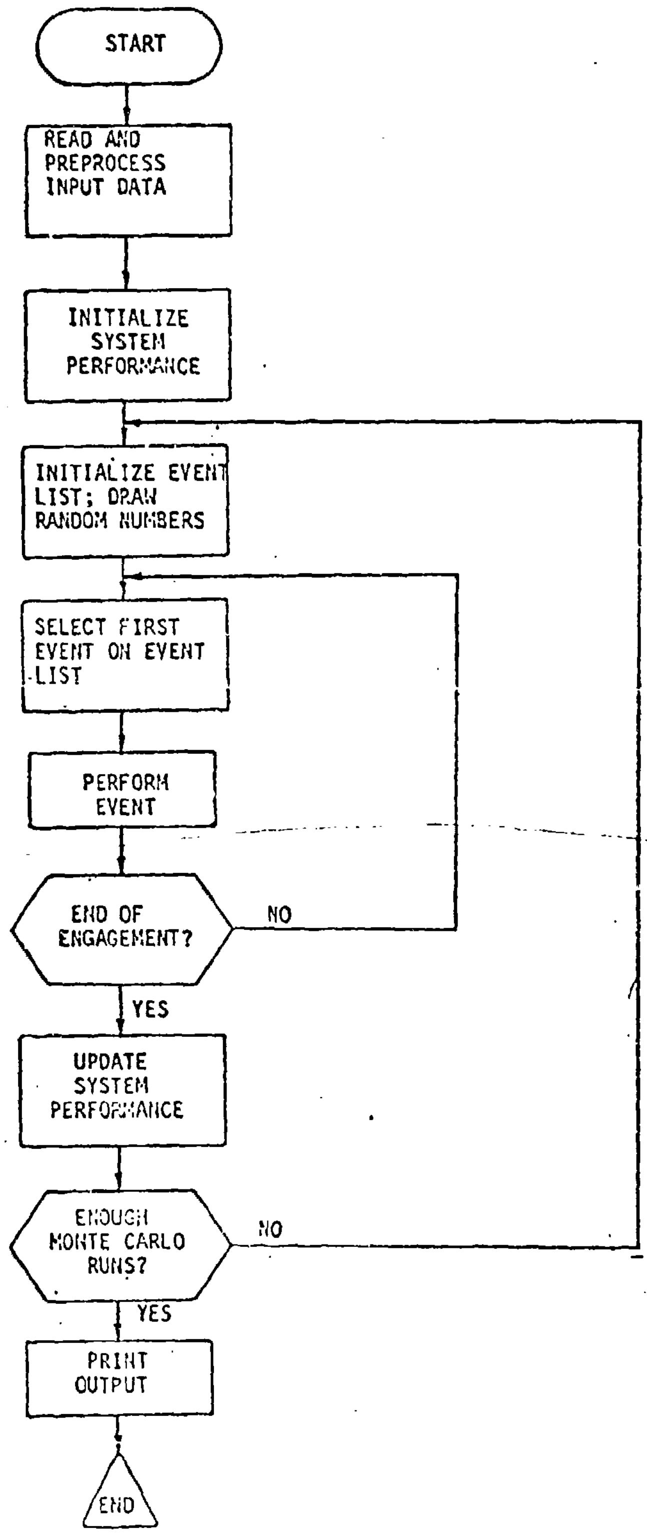
The inputs are in three categories:

1. Defense Characteristics

Locations, shapes, vulnerability (to each target type), and value (to the defense) of the defended assets.

Locations, primary target lines, and missile inventory of each Fire Section.

BASIC SAM-D FIDOC MODEL



Search sector, search scan time, and single hit detect probability (for each target type) for each Fire Section.

Missile flyout characteristics (time to reach various range/altitude points), and single-shot probability of kill (for each target type).

Missile launch constraints due to reaction times, required delay (due to SOP for example), or saturation of the Fire Control Group radar.

2. Attack Characteristics

Threat group vehicle types (e.g., aircraft, air-to-surface missile, ...), weapons and time(s) of attack, and dynamic limits.

Threat group vehicle paths (x(t), y(t), z(t)).

The defended assets to be attacked by each threat group.

3. FIDOC Characteristics

Specification of the conditions under which the FIDOC will cause a missile to be launched vs a threat. This includes specifying the Method of Fire (e.g., Shoot-Estimate-Shoot, Shoot-Shoot, etc), the maximum engagement range allowed for specific type target, etc.

If the user of the SAM-D FIDOC Model determines that certain inputs will be rarely changed (for example, the missile flyout characteristics) then the model can be made more efficient and convenient by handling such inputs as subprograms rather than data to be input for each run.

The INPUT routine of Fig. 2 formats the input data specified by the user. Its function is to put the user inputs into a form suitable for use by the other major routines of the program. The INPUT routine is designed, to the extent possible, to place the burden on the computer of formatting the input data. This routine will also initialize the event list and "draw" all the required random numbers required for one Monte Carlo run. This will permit duplication of runs to permit a run by run comparison of outputs using alternate firing doctrine policies. The initialization of the event list will accomplish the following functions:

1. Put end of engagement on event list at stored end time.

2. Put attack on defended asset on event list at stored attack times for each defended asset.

3. Put search on event list at stored initial time.

4. Initialize system state

A) All threat groups have status - alive, but not yet identified.

B) All threat groups are on the undetected group list with zero cumulative probability of detection.

C) All area assets 100% surviving. All point assets in status - alive.

D) All SAM's in status - alive but no launch planned.

5. Pick a launch random unit* for each SAM.

6. Pick an intercept random unit for each SAM.

7. Pick a detection random unit for each threat group.

8. Pick a destruction random unit for each (group, point defended asset attacked by the group) combination.

SAM-D ENGAGEMENT EVENTS

As previously stated there have been several critical events which have been identified as points during the search, track, and engagement functions at which some action must be taken in the SAM-D FIDOC Model. For purposes of understanding a brief review of two of the terms used in defining these events is necessary.

Target Evaluation Weapon Assignment (TEWA) - the SAM-D FIDOC function which accomplishes missile allocation. This function will rank the order of all the threats which are in the track file and then determine which threat targets are to be engaged and the sequence and time at which the threat targets should be engaged.

Target via Missile (TVM) Guidance - the terminal guidance mode which is used on a time shared basis between missiles.

The following list includes all the critical events that require scheduling for each run of the SAM-D FIDOC Model. The execution of one of these events may determine the next time that another event in the list is scheduled to occur. The events are listed in the normal sequence in which they would occur during an actual SAM-D engagement. A detailed explanation of the actions taken at each event will follow.

1. Search
2. Classification and Identification Complete
3. Call TEWA
4. Launch
5. Launch Assessment
6. Intercept of Threat
7. Attack on Defended Area
8. End of Engagement (Pseudo event to end Monte Carlo run)

* A random unit is a random number uniformly distributed between 0 and 1.

When the time is reached which requires that a particular event be performed, a series of computations and decisions is accomplished. It is at these particular times that all the various algorithms which have been developed for the SAM-D Firing Doctrine are executed. These algorithms will be varied and their effectiveness evaluated from run to run of the model.

SEARCH

1. For each group on undetected group list:

A) Find P_d, probability of detection during last interval, from probability of detection list for the group.

B) Update cumulative probability of detection P_C:

$$P_C = P_C^{Prev} + (1 - P_C^{Prev})\, P_d$$

C) Compare P_C to detection random unit.

D) If random unit is less than P_C the group is detected; furthermore all groups linked to the given group are also detected. In this case remove appropriate groups from undetected group list and put "classification and identification complete for this threat" on event list at present time plus classification and identification time increment.

2. Unless undetected group list is empty put search on event list:

A) Use normal search increment in absence of emergency (maximum number of missiles in flight).

B) Use emergency search increment in presence of emergency.

CLASSIFICATION AND IDENTIFICATION COMPLETE

1. Update system state to reflect threat identification and classification.

2. Put "call TEWA" on event list at next time when at least one guidance command channel is free.

CALL TEWA

1. Update FIDOC track file.

2. Call TEWA.

3. Update system state with results from TEWA.

4. Put launches on event list at appropriate times for all new launches computed by TEWA.

5. Change times of launches on event list for all launch times changed by TEWA.

LAUNCH

1. Compute intercept time list for SAM by calling guidance.

2. Put launch assessment on event list at present time plus assessment time.

LAUNCH ASSESSMENT

1. Compare probability of launch success to SAM launch random unit.

2. If random unit is less than probability, launch is successful.

3. If launch is unsuccessful update system state accordingly and put call TEWA on event list at present time.

INTERCEPT OF THREAT

1. Compute time SAM has been in TVM prior to present intercept time.

2. Compute probability of intercept from intercept position, threat vulnerability and time in TVM.

3. Compare probability of intercept to SAM intercept random unit. If random unit is less than probability, intercept is successful; in this case update system state accordingly.

4. Put "call TEWA" on event list at present time plus time required to assess intercept.

ATTACK ON DEFENDED ASSET

For a Point Asset:

1. Determine probability of destruction from vulnerability to threat type and size of attacking group.

2. Compare probability of destruction with appropriate destruction random unit.

3. If random unit is less than probability defended asset is destroyed; in this case update system state.

For an Area Asset:

1. Determine percent of defended area destroyed from vulnerability to threat type and size of attacking group.

2. Update system state to reflect increased percent of defended area destroyed.

OUTPUTS FROM THE SAM-D FIDOC MODEL

The OUTPUT routine of Figure 2 formats the data to be presented to the user. Detailed output data are available, at the user's request, describing the engagement statistics at each time increment. Summarized outputs can also be generated at engagement times specified by the user. Examples of summary information include the probability distributions for the number of surviving aircraft and the number of SAM-D missiles employed up to the specified time in the engagement.

The outputs that can be generated by the SAM-D FIDOC Model include the following:

Probabilities of survival of vital areas and SAM-D system elements.

Probabilities of survival of targets.

Probability distributions of destroyed targets, missiles launched by each FS, and missiles remaining at each FS.

Probability of weapon commitment to each target by each FS.

Marginal return for each FS (expected number of targets killed/expected number of missiles launched).

These outputs can be generated at user-specified intermediate times during an engagement as well as at the terminal time of the engagement.

AD P000622

LINES OF COMMUNICATIONS TARGETING FOR GROUND OPERATIONS

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1. Background

In the early 1960s, algorithms were developed for targeting air strikes against enemy lines-of-communications (LOCs). Air strikes conducted during the mid 1960s in Vietnam met with limited success due to enemy proliferation of LOCs and less than optimum interdiction points along those LOCs. Evaluation of air interdiction campaigns from World War II and Korea demonstrated that the interdiction area should be commensurate with the size of the force involved. It is more desirable to apply a sustained force against a small system than to attack a larger system with an inadequate force that cannot achieve a desired damage level. As target selection must take maximum advantage of natural barriers so as to deny the enemy the use of bypasses or alternate routes, it must be recognized that even if all targets are hit and complete interdiction of normal traffic is achieved, the enemy will still be able to move a limited quantity of supplies around interdicted points.[1] As sufficient supplies to maintain a defensive posture are normally stockpiled or can be supplied by bypassing interdiction points, the purpose of an interdiction campaign should be to disrupt enemy LOCs to such an extent that the enemy would not be able to contain a determined offensive by friendly forces or be able to mount a sustained campaign himself.[2] Additionally, a single strike by a limited attack force should inflict the maximum amount of damage on the LOC within that force's capability.

2. Scope

This paper displays a method of single strike targeting. It may be used when the area under study is limited in total area and by topography (thus limiting enemy LOCs). An optimum interdiction point within an enemy LOC network can then be determined and targeted for interdiction by a limited ground combat force. The location of the target is constrained by high enemy threat areas and lack of intelligence as developed in a limited scenario, which approximates a real life situation. The target location will be determined in part by the use of algorithms originally developed for air interdiction.

3. Criteria

Studies of interdiction effectiveness normally rely upon quantitative measures of merit. To determine optimum interdiction targets the following information is generally required:

(1) Overall capacity of the logistic system

(2) Redundancy of LOCs

(3) Repair capability

(4) LOC closure and reduction in the flow

(5) Level of supply[3], and

(6) Enemy protection capability

A single mode system of transportation routes such as a road can be represented by a network of nodes and directed arcs. For this highway system, a node is the intersection of two or more roads and an arc represents a road segment joining two nodes. In a one way segment, the beginning node (source) is the point where the traffic enters the segment and the ending node (sink) is the point where traffic leaves it.[4] The source or sink can in reality be indeterminate areas which are considered as points for computation purposes. Each arc has certain parameters: flow capacity (the upper bound on flow), lower bound on flow, and cost per unit flow. The flow can be in tons/day, trucks/hour, or any other appropriate measure. The cost per unit flow could be in dollars/ton moved, man-hours/vehicle, and vehicle hours.

Strike effectiveness is based primarily on the degree to which it reduces the usefulness of the LOC to the user.

Strike effectiveness may also be measured, if information is available, in the increased enemy man-hours required to increase defenses on the LOC. In this paper, the LOC is represented as a simple network in which flow is from West to East. User effectiveness of the LOC is measured by determining the maximum flow from one node (source) to another (sink). This is realistic when the user is physically limited by the ability of his transport system to handle traffic.

4. Flow Values

The flow pattern in a network can be found with the following algorithm where each arc (i,j) has an upper bound (u_{ij}) and a lower bound (l_{ij}) on its flow and a cost (c_{ij}) which is the cost per unit of flow (in terms of tons of supplies per day). If x_{ij} represents the flow on arc (ij) then

Find flows, $x_{ij} \geq 0$ that minimize

$$(1) \quad \sum_{ij} c_{ij} x_{ij}$$

subject to

$$(2) \quad l_{ij} \leq x_{ij} \leq u_{ij} \quad \text{all } i,j$$

$$(3) \quad \sum_{j} x_{ji} - \sum x_{ij} = 0 \text{ all } i$$

The first expression represents the total cost of the flow pattern, the second states that the flow on each arc must be between its lower and upper bounds, and the third expression states that the flow into any node must equal the flow out of it (from Fulkerson's "out-of-kilter" algorithm as stated by Wollmer).[5] Estimating the road capacity or flow also can be derived from direct observation and intelligence reports received at a later date.

After arc flows have been determined, the maximum strike value of each arc is computed.[6] The value of the arc (v_{ij}) equals the cost of that one arc being struck and no other arcs struck in the network (k_{ij}) minus the cost if no arcs are struck in the network (k) times the repair time for the arc (t_{ij}) plus the repair cost of the arc (r_{ij}).

$$v_{ij} = (k_{ij} - k)\, t_{ij} + r_{ij}$$

The arc to be struck is determined by calculating the strike value for each arc. In a more complicated LOC another one strike algorithm can be used to determine the arc of maximum strike value without calculating the strike value for each arc.

A network is then developed in which some flow values are determined by observation and intelligence and others by determining flows that would minimize the enemy's cost. Certain scenario constraints will not allow the more obvious arcs or nodes to be struck.

5. Scenario and Data Inputs

Within a 50 km by 50 km area, enemy forces have established a LOC which has one primary source and several exit points. The road network LOC traverses this area with the movement of supplies from west to east. Certain areas within this LOC cannot be struck due to heavy enemy threat, AAA or enemy infantry personnel. The roads are of poor soil and laterite with a high clay content, passible only in the dry season. The length of each road segment is less than 20 km and the total length of the roads within the network is 320 kms. Intelligence reports indicate that the enemy logistics personnel have only 70 trucks, 50 of which are useable at any given time.

Initially, friendly forces have only a 50-man reinforced platoon which can be used to strike the LOC. Furthermore, interpretation of sensor reports indicates that 25 trucks are available at Point S and 25 trucks work from Point G. The supply rate per segment (s = tons of supplies moved per operating day) is equal to the number of trucks operating on a segment (n) times the truck payload (P = 4 tons) times the round trips per operating day (X = 1) (see Annex A).

$$S = nPx$$

From the above flow values, scenario and data inputs, the strike value of each LOC segment is computed. (see Annex B) Where enemy strength is too great a threat, the next lower segment is targeted.

6. Conclusions and Recommendations

The strike values of the link segments indicate that a single strike would be most effective if conducted on the link segment which has the highest value and is located outside of the major threat areas. If this were a true life situation, a strike would be targeted on the specific link segment. It could be recommended by a reconnaissance battalion's S-2 for approval by higher headquarters.

7. Limitations

This method of determining targets for limited ground operations is effective only in a limited geographical area in which the enemy's LOC is generally known and his relative strength and general operating procedure can be approximated.

FOOTNOTES

1. Hawley, p. 16.
2. Ibid, p. 12.
3. USAF ACS-SA, p. 9.
4. Wollmer and Ondrasek, p. 3.
5. Wollmer, p. 3.
6. Ibid, p. 9.

ANNEX A - ONE WAY SHUTTLE OPERATIONS

The equations for one-way shuttle operations are:

(1) $$p = xt$$

(2) $$t = \frac{2ks}{V} + \frac{knd}{500V} = \frac{p}{x}$$

(3) $$n = \frac{500V}{kp} \frac{p}{x} - \frac{2ks}{V}$$

(4) $$N = \frac{na}{K}$$

(5) $$S = nPx$$

where:

a = number of segments in a link

d = operational (average) lead between trucks (m)

K = truck availability factor

k = en route stop factor

N = total number of trucks assigned to a link

n = number of trucks operating on a segment

P = truck payload

p = operating period (hr/day)

S = supply rate (tons forward per operating period, i.e., calendar day)

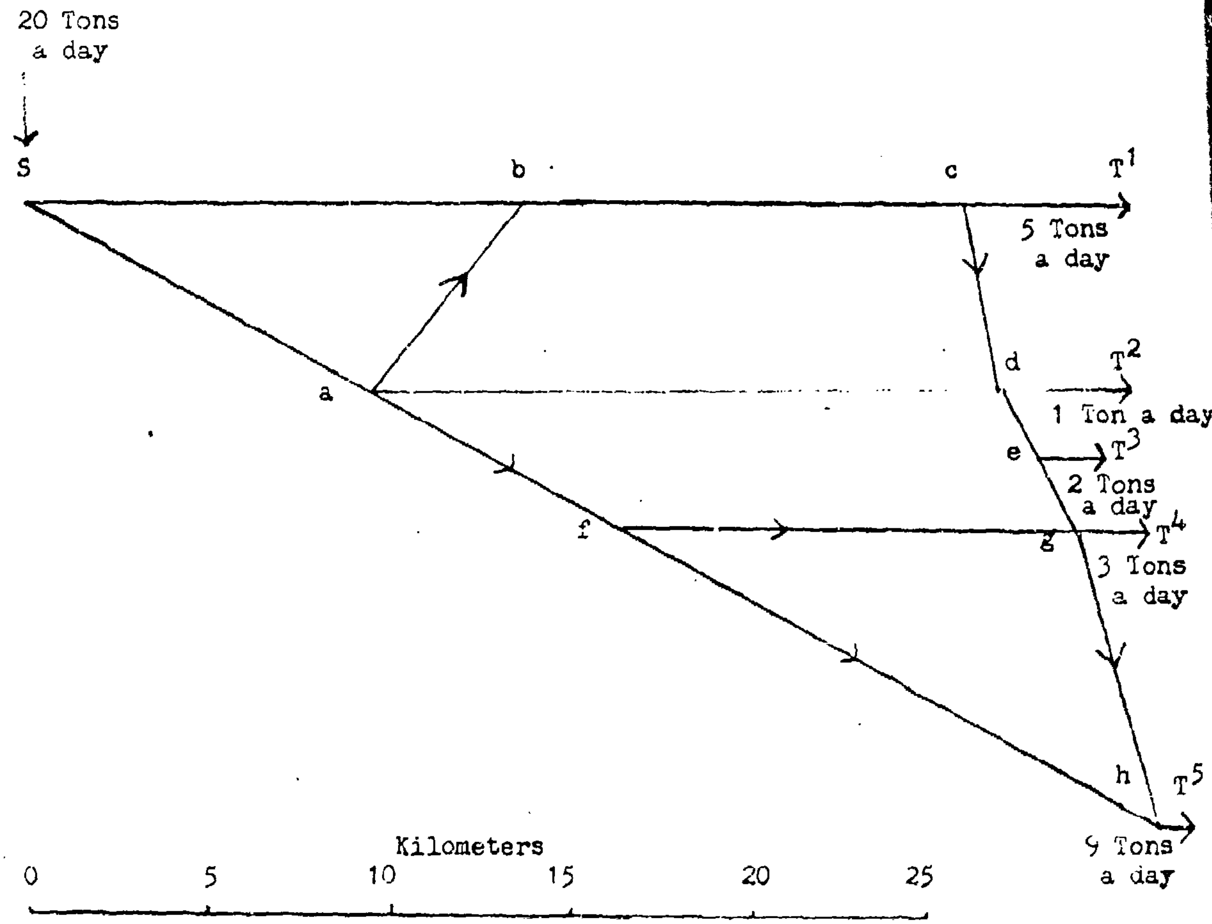
s = length of segment (km)

t = turnaround time on segment (hr)

V = average truck speed while moving (km/hr)

x = round trips per operating period

ANNEX B - LOC Network



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A HIERARCHICAL STRUCTURE OF MODELS FOR THE ANALYSIS OF LAND MOBILITY SYSTEMS

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INTRODUCTION:

The technology of land mobility is broad and diverse. It is concerned with everything from the development of new fasteners to the fielding of a totally new truck fleet or family of combat vehicles. Its proper tools run the gamut from standard, detailed engineering disciplines to modern operations research and systems evaluation methods.

Despite the explosive expansion since World War II of operations research and systems analyses as critical elements in high-level decision-making, the need for credible models which integrate detailed engineering capabilities in land mobility into comprehensive measures of performance has only recently been recognized. Systematic guidance of developments within the technology area has suffered. More important, the impact of land mobility upon military problems has been but poorly represented in the decision-making process. On the other hand, this belated perception offers a singular opportunity. Starting with a relatively clean slate, we have the chance, in principle at least, to develop needed models as a continuing, cumulative research task within the context of a rational system of models designed to meet a broad range of foreseeable needs.

CREDIBILITY--THE CENTRAL ISSUE:

In this paper we propose a framework for a deliberately supportive hierarchy of models and related experimental procedures to meet the needs of land mobility design, development and evaluation. Central to the concept of this proposed structure is the clear necessity to maximize the credibility of those models which predict behavior of complex systems. Lack of an acceptable level of credibility in such models appears to be at the root of present disenchantment in many quarters with systems analyses and simulations generally.

DECISIONS AND VALIDATION:

The primary object of modeling and simulation is to predict system behavior in quantitative terms, whether deterministic or stochastic.

Engineering models use physical laws and hard data to predict relatively simple measures of performance of engineering systems, such as vehicle speeds and reliability, or hit probabilities. Such models can be validated to a high degree (although they not always are).

Once the system under consideration begins to include significant human judgment calls and elements of scenario, the measures of its performance become decision-dependent, highly aggregated and more abstract in form. And predictions of performance become more difficult to validate by means of simple experiments. Quantities which appropriately characterize the functioning of a system of this broad scope constitute measures of effectiveness.

Interpretation of any set of performance or effectiveness measures to reach a technical decision requires judgment as to their relative military importance. Such judgments may be exercised in several ways:

- The decision makers may examine the data at hand and make a subjective evaluation integrating diverse influences on the basis of experience, wisdom and other intangibles.

- The decision makers (or their technical advisors) may attempt to formalize and impart an aura of rigor to the judgment process, by formulating numerical weighting factors expressing the supposed relative importance of various performance or effectiveness measures, leading to an "index of merit". This procedure is generally nonsense, whether applied with or without bias.

- The decision makers may make those decisions necessary to submit the data to further analyses, in which other influences are examined and other measures of performance or effectiveness are introduced. No matter how far the analyses extend, however, the final decision will require a judgment of either the first or second (hopefully the first) kind.

Note that the "decision makers" should be different at different levels of system aggregation. A major problem in the credibility of many past simulations appears to have been that in formulating a model, and in setting up data bases and scenarios, decisions have been made by indians that should have been left to the discretion of chiefs. To compound the offense, these decisions have often been buried without headstones deep in the computer program. Making all significant decision and judgment points both identifiable and accessible to the proper decision makers appears necessary to further progress in simulation.

BASIC MODEL SYSTEM REQUIREMENTS:

The perceived requirement for maximum credibility thus leads directly to two obvious but not trivial features which are essential to a viable system of models.

- The hierarchy of models must be designed to allow maximum validation, and, (almost as a corollary),
- the models must make a clear distinction between engineering predictions, and those predictions whose outcomes depend upon human judgments made during the course of the activity being modeled.

Primarily in response to validation needs, it appears essential that the hierarchy of models be structured from the outset to interface with specifically compatible experimental procedures, in effect constituting a two-part interactive methodology in which:

- analytical procedures are used for predicting and optimizing system behavior at various levels of system complexity, and
- experimental procedures are utilized to supply hard data to formulate, validate and apply the analytical procedures.

Figure 1 illustrates an idealized relation between analytical and experimental procedures to support development of a new land-vehicle system from a recognized need through to a procurement decision. The sinuous path uses analytical procedures to guide the development at each stage. Just as regularly, it touches base with the real world through tests which validate previous analyses, and feed critical hard data forward to the next level of analysis.

Characteristics of the supportive experimental procedures will not occupy us further in this brief paper. Before leaving the subject, however, we would point out that, by and large, these characteristics will be dictated by the requirements of the analytical methods. While these will not normally require extensive new test equipment, they will often require some substantial changes in test viewpoint, and in the prerogatives of test agencies.

The analytical methodology has the generic form of a system of validated, comprehensive computerized models. The scope of the complete system of models is extremely broad, both in terms of system complexity and of levels of behavior to be predicted. This breadth leads to further functional requirements relative to the structure of the desired system of models.

The structure cannot be monolithic. The actual military value of a new tank engine, for example, should theoretically be reflected in the outcome of a war. In practice, of course, common sense prohibits the examination of such a detail in such cosmic terms, and dictates that evaluations be restricted to a scale and resolution at which the effects of engine change are not lost in the noise level of the procedures. The same good sense also counsels, however, that it is not sufficient that the new engine merely demonstrate some measurable engineering improvements in the test cell, or even in a trial installation. The operational effects of the engineering improvements must be ascertained before a commitment is made. In short, to be acceptable, modeling procedures must allow examination of the influence of the new engine (or other innovations, larger or smaller) upon system behavior at an appropriate resolution.

The modeling system must also permit utilization of the results of higher resolution computations as inputs to broader, lower resolution analyses, rather than burdening the latter with excessive detail. Returning to the tank engine example, it would be appropriate first to examine the engine's influence upon tank mobility and agility performance. Following this, the effects of resulting changes in tank mobility/agility performance upon the outcome of small unit actions might be evaluated. This might be a reasonable point at which to make a decision, or the analysis might continue a step further and examine the effects of the predicted changes in small-unit outcomes upon division-level operations.

The structure of the model hierarchy, and the interfaces among the models within it, should thus be such that not only can a given examination readily be carried to the level of analysis needed for decision making, but also that the effects of changes in performance or effectiveness at each level can be communicated in compatible terms to the next higher level without involving the latter with inappropriate detail. Figure 2 illustrates schematically the supportive structure which is needed.

SUMMARY GUIDELINES:

At this point we may summarize major considerations in structuring a supportive hierarchical system of models for land mobility technology, including some which appear to need no elaboration. The considerations are as follows:

- the pressing need for maximum feasible model validation and experimental verification,

- the necessity to separate engineering and human judgment decision points, and to make the latter both visible and accessible,

- the essential requirement that the system of models be developable on a continuing research basis responsive to innovations at all levels from components to doctrine,

- the logical necessity of the models being adaptable to a wide range of applications,

- the pragmatic aspect of costs of model development and operation which will determine whether or not the system is in fact developed and used, and

- the desirability of being able to utilize measured performance data in place of analytical values during successive stages in the development of new systems.

These considerations clearly dictate a highly modular structure which can accept and aggregate required information according to the needs of any of several levels of analysis.

A GENERALIZED STRUCTURE:

A schematic of a general structure which satisfies these objectives is shown in Figure 3. Three hierarchical levels of models are illustrated:

- Subsystem level models, used in the design and engineering of subsystems.

- Elemental system level models, which predict various measures of performance of a particular end item.

- Total system level models, which are used to predict the contribution which a particular end item with specific performance characteristics may make to the military effectiveness of a land mobile system in combat or combat support.

A feature to be especially noted is that major human judgment inputs are specifically identified and reserved as inputs to the highest level of models in the hierarchy (Scenario, Doctrine and Tactics as inputs to Total System Level Models). This, of course, does not guarantee that some minor human decisions may not (sometimes necessarily) be involved in lower-order models, but, with attention to flagging these and making them accessible to the model user, the scheme should be workable.

Figure 3 stresses that, as noted earlier, the essence of the modeling process is quantitative prediction of the behavior of systems at each level of aggregation and complexity. Addition to the predictive capability of

appropriate logic and feedback loops converts the modeling procedure per se into a tool for design and for the study of system sensitivities. Several such possible loops are illustrated. Development of logic and procedures for practically implementing interaction feedback of the form illustrated (especially, for large systems, within reasonable computing time and costs), is a materially desirable adjunct to the creation of the comprehensive predictive modeling system. And it is certainly obvious that the timely development and productive utilization of such feedback methodology will be greatly facilitated by the existence of an internally consistent and comprehensive model structure.

Finally, the figure emphasizes that credible modeling requires the support of an extensive and compatibly structured data base from which characterizations of equipment, men, environments, and, when desired, various elements of scenario, are drawn, and to which significant predictions are returned for future reference. Realistic characterization of data base elements, especially those related to man, environment and all facets of scenario, is an intrinsic and crucial part of the modeling job. Such characterization involves not only the collection of relevant data, but the abstraction from real world entities into models which at once preserve a suitable degree of realism and meet the needs of system models for specifically quantified inputs.

In the following few paragraphs, some further features of the structure are discussed briefly.

Total system-level models comprise those elements which are closest to the final decision-making process where large system decisions are involved. They obtain inputs from lower-order models and from scenario elements characterized by the model user and/or drawn from the data base.

Each total system-level model predicts measures of one or more aspects of total system performance under a set of circumstances of considerable breadth. As suggested in Figure 2, total system-level models may vary widely in scope and related resolution. For present purposes those of relatively limited scope and correspondingly higher resolution are considered to comprise a subset designated as subtotal system models. The remainder are designated as total system models.

Total system models. Validation of total system models is impossible. Credibility of results depends wholly upon the validity of input data, upon the visibility and accessibility of appropriate decision points, and upon the visibility and acceptability of the model logic.

The situation of total system models for land mobility applications, relative to the ideal illustrated in Figure 2, was summarized in a broader context in May 1971 by the Department of the Army Models Review Committee* as follows:

> "In order to provide a degree of logical consistency throughout the analyses of Army systems, it is necessary that significant variations in the results at any one level be reflected as input to the analyses in higher level studies ... Although this need to feed information up the chain is well recognized, no links between levels of models really exist at this time."

In addition, none of the total system models currently in use is at present logically responsive to changes in land mobility at the elemental system level. In these models mobility influences constitute a part of the scenario input, and are assigned largely on the basis of military experience and judgment. The current state of land mobility technology can make these inputs more objective. Clearly, total system models which have no mechanism which consistently reflects changes in the land mobility of elements of the system are unsuitable for making land mobility decisions, or for providing data needed to guide suboptimizations within the scope of land mobility technology.

The construction of total system models is beyond the scope of land mobility technology. However, development of a variety of validated subtotal inputs for such models, reflecting the full range of land mobility technology, clearly is. So too is the establishment of working links to the total-system modeling community, to insure proper use of these data, and the feedback needed to implement and exploit land mobility modeling.

Subtotal system models. Subtotal system models lie at the major interface between a total system simulation and the technology areas with which that system deals. They examine a single major subset of total system performance plus a reduced representation of scenario, such as mission profiles. They may deal with one or a modest number of nominally identical elemental systems (i.e., a fleet of M35, 6x6 2-1/2 ton cargo trucks), or mixes performing essentially one broad task (a tactical support company).

Subtotal system models have two functions. First, they aggregate more detailed elemental system performances as input data for total system models. Second, they provide a basis for evaluating and suboptimizing

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elemental system design. In the latter use they require guidance from total systems analyses as to the military value associated with changes in their particular measures of performance.

Subtotal system models can be given limited experimental verification through the agency of carefully designed field tests and close analyses of properly formulated field reports. Even so, their credibility still depends heavily upon the degree of validation and realism of the elemental system performance, environmental and scenario data utilized. During the later stages of a system development, important segments of the input data can and should be actual measured elemental system performances. However, because land mobility is so entangled with the endless variability of environment and mission, even these hard data usually will not be complete enough to permit a full evaluation without repeated recourse to the elemental system models. Accordingly, validation of elemental system models is at all times critical to the utility of subtotal system models.

Elemental system models. An elemental system is a single mechanical unit of a total system which is itself a system of lower order, such as a tank or an ACV. Elemental system models predict measures of one major performance aspect of an elemental system at a given time and place.

Elemental system models are central to land mobility methodology. By their use the design engineer determines, in specified environmental situations, the net, single-unit performance of feasible configurations among interactive subsystems. They also directly serve the needs of subtotal system models for hard, realistically aggregated engineering performance data, and in turn, require from subtotal system models quantitative guidance for elemental system design optimization.

The critical position of the elemental system models in the mobility model hierarchy demands that each be highly verified. Elemental system models are at the highest order of aggregation of subsystem performance measures which is independent of major human judgment factors, mission, doctrine and scenario. Accordingly, it is entirely feasible to verify their realism and quantitative reliability by experimental validation over a wide range of system and environment configurations. Continuing attention to this need is essential to the credibility of higher-order simulations.

Subsystem models. Subsystem models are the principal interface between physical, engineering research and systems level models. In land mobility technology, they express the engineering performances of automotive and mobility support subsystems by the tedious but relatively straightforward organization of valid engineering equations and data:

performance maps for specific engines, or propellers; traction of a given tire as related to load, inflation, slip, soil strength, speed; failure rates of particular parts and components in controlled shake tests; etc. The range of detail conceptually embraced is vast. Needless to day, the reliability of higher-level models depends to a significant extent upon the soundness of these many foundation blocks.

A HIERARCHICAL STRUCTURE FOR LAND MOBILITY ANALYSIS:

Application of the general approach we have outlined to the problem at hand; i.e., the design of a system of models for the analysis of land mobility systems; leads us to the schematic hierarchy shown in Figure 4. This figure elaborates only the predictive heart of the system, without any of the many possible and desirable feedback loops. It also indicates the relation of the model hierarchy which lies within the scope of land mobility technology to still broader simulations which it should support and be supported by. It is obvious that the structure illustrated is still highly stylized. There is, for example, considerable potential for further modularization at hierarchal levels intermediate to the levels presented.

Implementation of the scheme outlined in Figure 4 is already under way. Present status is grossly indicated in Figure 5. The principal elements shown as operational are specifically the result of the AMC Ground Mobility Research Program, under which the research work of many years on the performance of ground-crawling vehicles was consolidated into a first-generation Ground Mobility Model (currently designated AMC-71).* As a matter of fact, much of our thinking about larger systems of models is the result, direct and indirect, of our experiences (mostly happy) in the development, validation and early applications of AMC-71.

The same experience has taught us that the development of a system of reliable, credible models is properly a continuing research task. The process is evolutionary and highly iterative. Typically, modeling at any level begins with a logic which generates its own imperatives for data. In an orderly world these requirements are met by a timely aggregation from existing sources and, as needed, from further research. Implementation is followed by repetitive verification, validation and refinement of model structure and data--until the required level of confidence is achieved. Where substantial needs for specific models can be forecast, it is folly to leave their development to *ad hoc* creation in a "crash" environment.

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*"The AMC-71 Mobility Model", USATACOM Report No. 11789, July 1973.

CLOSURE:

The preliminary and highly schematic structure which we have presented in Figure 4 appears adequate to give some coherence and direction to land mobility modeling in the immediate future, and, it is hoped, to provide some guidance in the formulation of a more detailed plan. It is clearly not yet the definitive long-range plan which we need.

Careful development of a detailed, logical structure, responsive to the needs both of land mobility technology and of increasingly critical and complex total systems simulations, is the next order of business. Timely development of such a plan is an important task, and one of great potential rewards. It presents a complex problem whose orderly solution will require the best quiet thinking of many people, of many interests and at many levels of command, military and civilian.

To be meaningful, such a plan must be supported by a firm policy commitment to develop, refine and validate models implementing the plan on a continuing research basis, so that future modeling effort will become cumulative, and the resulting models will become ever more accessible as tools for innovative design, for management, and for the development of advanced tactics, doctrine and strategy.